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THE SECOND REPORT
ON THE STATE
OF THE WORLD'S
FOREST GENETIC RESOURCES

FAO COMMISSION ON GENETIC RESOURCES FOR FOOD AND AGRICULTURE
ASSESSMENTS • 2025

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

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Forests and trees contribute to the FAO Strategic Framework 2022-31 founded on the Four Betters: better production, better nutrition, a better environment and a better life, leaving no one behind. They help maintain soil fertility, protect water catchments, provide nutritious wild foods, mitigate the impacts of the climate crisis and produce renewable products that support livelihoods.

At the heart of these contributions are forest genetic resources: the heritable materials maintained within and among tree and other woody plant species that are of actual or potential economic, environmental, scientific or societal value. Forest genetic resources are indispensable for enabling forests to adapt to stressors such as drought, pests and diseases and thus for the long-term health of forests and the well-being of people.

Drawing on submissions by 77 countries, which together represent more than three-quarters of the world's forests, *The Second Report on the State of the World's Forest Genetic Resources* provides a global assessment of the status and trends of forest genetic resources. Prepared under the guidance of the Commission on Genetic Resources for Food and Agriculture, the report also analyses the progress made in implementing the Global Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources.

The report, an update of the 2014 edition, provides a detailed account of the state of the world's forest genetic resources and their conservation and sustainable use. It stresses the vital role of these resources in addressing food insecurity, malnutrition, poverty, the climate crisis and biodiversity loss. Finally, it identifies key actions to ensure that they are conserved and used sustainably for the benefit of current and future generations.

Notwithstanding many positive developments, forest genetic resources are threatened by multiple factors and although notable progress has been made in developing policies and strategies for their conservation and sustainable use, significant gaps remain. Strengthening international collaboration, enhancing capacity and improving the alignment of national policies with global frameworks are crucial. Fostering the full and effective engagement of women, youth, Indigenous Peoples, local communities, civil-society organizations, the private sector and funding partners, as well as stakeholders from all other sectors is also vital. This calls for integrated and holistic 'whole-of-government' and 'whole-of-society' approaches.

FAO is committed to the conservation and sustainable use of forest genetic resources, in line with its mandate. Investing in forest genetic resources and managing them sustainably will strengthen their resilience, while also increasing productivity and developing new products.

The challenges are immense, but so are the opportunities. Together, we can harness the potential of forest genetic resources to promote transformation to more efficient, more inclusive, more resilient and more sustainable agrifood systems for a better future for people and the planet.

QU Dongyu
FAO Director-General

Acknowledgements

The preparation of this report relied on the inputs and expertise of many individuals and the collaboration and support of governments and partners. FAO takes this opportunity to acknowledge all these contributions.

Submissions by 77 countries comprised the primary sources of data and information used in the report, supplemented by scientific literature. FAO thanks the governments and individuals involved, particularly the National Focal Points, for their efforts in gathering the data and providing complementary written information. FAO also thanks those who contributed to the preparation of reports submitted by organizations and regional networks. The report was made possible by financial support provided by the governments of Canada, Germany, the Kingdom of the Netherlands, Norway and Switzerland and the in-kind contributions of the Government of France.

The report was prepared by FAO's Forestry Division in collaboration with external experts. The reporting process and core team were coordinated by Jarkko Koskela, with assistance from Didier Paradisi and Branislav Trudic. Damien Bertrand (seconded by the Government of France until July 2021) contributed to the organization of regional workshops for the National Focal Points. Administrative support was provided by Roberta Piferi and Veronica Topalo. The reporting process was initiated under the supervision of Sheila Wertz-Kanounnikoff and concluded under that of Thomas Hofer.

Report preparation was facilitated by former and current secretaries of the Commission on Genetic Resources for Food and Agriculture, Irene Hoffmann and Manoela Pessoa De Miranda, respectively, and supported by Ghislaine Gill, Dan Leskien and Suzanne Redfern from the Commission's Secretariat. The guidance provided by the Intergovernmental Technical Working Group on Forest Genetic Resources throughout the preparatory process was greatly appreciated.

A total of 43 individuals contributed to the write-up of the report, as listed below with their affiliations. Text boxes were prepared by chapter authors unless otherwise indicated. Didier Paradisi and Branislav Trudic analysed the country data and taxonomic information, respectively, for various chapters. David Boshier reviewed the entire manuscript. Thomas Hofer, Dan Leskien, Anssi Pekkarinen, Suzanne Redfern, Elaine Springgay and Tiina Vähänen also contributed to the review process. Comments provided by Christel Palmberg-Lerche and Oudara Souvannavong are gratefully acknowledged.

The draft report was made available for review by members and observers of the Commission on Genetic Resources for Food and Agriculture, and comments were received from Argentina, Brazil, Burkina Faso, Canada, Denmark, Finland, Germany, Japan, the Kingdom of the Netherlands, Poland, the Russian Federation, Spain, Sweden, Switzerland and the United States of America. The Alliance of Bioversity International and the Center for International Tropical Agriculture, the European Forest Institute and World Agroforestry also provided comments.

Alastair Sarre edited the manuscript and Roberto Cenciarelli did the layout.

Apologies to anyone who provided contributions but whose name has been inadvertently omitted.

Chapter/box	Title	Authors and contributors (affiliations are provided below the table)
PART 1 – THE CONTRIBUTIONS OF FOREST GENETIC RESOURCES TO SUSTAINABLE DEVELOPMENT		
Chapter 1.	The value and importance of forest genetic resources	Jarkko Koskela[a]
Box 2	Supporting healthy diets with food trees	Stepha McMullin,[b] Agnes Gachuiri,[b] Erick Ngethe,[b] Alice Karanja[b] and Ramni Jamnadass[b]
PART 2 – STATE OF DIVERSITY IN FORESTS AND OTHER WOODLANDS		
Chapter 2	State of the forests	Anssi Pekkarinen,[a] Örjan Jonsson,[a] Monica Garzuglia,[a] Lars Gunnar Marklund,[a] Anne Branthomme,[a] Xavier de Lamo,[a] Adolfo Kindgard,[a] Valeria Contessa,[a] Chiara Patriarca[a] and Erica Lupi[a]
Chapter 3	State of woodlands and agroforests	Ian K Dawson,[b] Alice Karanja,[b] Roeland Kindt,[b] Lex Thomson,[c] Erick Ngethe,[b] Stepha McMullin,[b] Jens-Peter B. Lillesø,[d] Ramni Jamnadass[b] and Lars Graudal[b,d]
Chapter 4	State of diversity of tree and other woody plant species	Malin Rivers,[e] Paul Smith,[e] Roeland Kindt,[b] Lynn Clark,[f] Maria Vorontsova[g] and William Baker[g,h]
Chapter 5	Genetic diversity in trees and other woody plants	Colette Blyth,[i,j] Andrew Lowe[i] and Sam Turner Blyth[k]
PART 3 – STATE OF FOREST GENETIC RESOURCE CONSERVATION		
Chapter 6	*In situ* conservation of forest genetic resources	Barbara Vinceti[l] and Evert Thomas[l]
Chapter 7	*Ex situ* conservation of forest genetic resources	Prasad S. Hendre,[b] Ramni Jamnadass,[b] Ian K. Dawson,[b] Alice Muchugi[b] and Lars Graudal[b,d]
PART 4 – STATE OF USE, DEVELOPMENT AND MANAGEMENT OF FOREST GENETIC RESOURCES		
Chapter 8	State of the use of forest genetic resources	Cuauhtémoc Sáenz-Romero[m] and Jarkko Koskela[a]
Box 9	Increasing the supply of high-quality tree seed in Ethiopia	Søren Moestrup,[b,d] Abrham Abiyu,[b] Kedra Mohammed Ousmael[d] and Lars Graudal[b,d]
Chapter 9	State of tree-improvement and tree-breeding programmes	Branislav Trudic[a] and Jarkko Koskela[a]
Chapter 10	Management of forest genetic resources	Jarkko Koskela,[a] Kenichi Shono[a] and Shiroma Sathyapala[a]
Box 12	Impacts of honey-gathering on tree populations in the Niassa Reserve, Mozambique	Laura K. Snook[l] and Natasha Ribeiro[n]
PART 5 – STATE OF CAPACITIES AND POLICIES		
Chapter 11	Institutional framework for the conservation, use and development of forest genetic resources	Ghislaine Gill[a] and Jarkko Koskela[a]
Chapter 12	International and regional cooperation on forest genetic resources	Didier Paradisi[a] and Jarkko Koskela[a]
PART 6 – CHALLENGES AND OPPORTUNITIES		
Chapter 13	Recommended actions for the future	Jarkko Koskela,[a] Didier Paradisi[a] and Branislav Trudic[a]

Note: a = FAO; b = World Agroforestry (CIFOR-ICRAF); c = University of the Sunshine Coast, Australia; d = University of Copenhagen, Denmark; e = Botanic Gardens Conservation International, United Kingdom of Great Britain and Northern Ireland; f = Iowa State University, United States of America; g = Royal Botanic Gardens, Kew, United Kingdom of Great Britain and Northern Ireland; h = Aarhus University, Denmark; i = Adelaide University, Australia; j = Universität für Bodenkultur Wien, Austria; k = University of Edinburgh, United Kingdom of Great Britain and Northern Ireland; l = Bioversity International; m = Universidad Michoacana de San Nicolás de de Hidalgo, Mexico; n = Universidade Eduardo Mondlane, Mozambique.

Abbreviations

AFOLU	agriculture, forestry and other land uses
AnGRFA	animal genetic resources for food and agriculture
APFORGEN	Asia-Pacific Forest Genetic Resources Programme
BGCI	Botanic Gardens Conservation International
BSO	breeding seedling orchard
Bt	*Bacillus thuringiensis*
CBD	Convention on Biological Diversity
Commission	Commission on Genetic Resources for Food and Agriculture
CIFOR–ICRAF	Center for International Forestry Research and World Agroforestry
DED	Dutch elm disease
DNA	deoxyribonucleic acid
EUFORGEN	European Forest Genetic Resources Programme
FGR	forest genetic resources
FRA	Global Forest Resources Assessment
GDP	gross domestic production
GFG	Global Forest Goal
GlobUNT	GlobalUsefulNativeTrees database
GM	genetic modification
GTKP	Global Tree Knowledge Platform
GTSBP	Global Tree Seed Bank Programme
GWAS	genome-wide association studies
ICRAF	World Agroforestry
IUCN	International Union for Conservation of Nature
IUFRO	International Union of Forest Research Organizations
LAFORGEN	Latin America Forest Genetic Resources Network
MAS	marker-assisted selection
NAFC	North American Forestry Commission
NBSAP	national biodiversity action plan
Ne	effective population size
NWFP	non-wood forest product
OECD	Organisation for Economic Co-operation and Development
OECM	other effective area-based conservation measure
OWL	other wooded land
PATSPO	Provision of Adequate Tree Seed Portfolios project
PGRFA	plant genetic resources for food and agriculture
POWO	Plants of the World Online
QTLs	quantitative trait loci
RBG	Royal Botanic Gardens, Kew
RNA	ribonucleic acid
SAFORGEN	Sub-Saharan African Forest Genetic Resources Programme
SDG	Sustainable Development Goal
SNP	single-nucleotide polymorphism
SoW-FGR	State of the World’s Forest Genetic Resources
TEAKNET	International Teak Information Network
TVET	technical and vocational education and training
USNA	Updated Silvics of North America

WCUPS	World Checklist of Useful Plant Species
WGS	whole-genome sequencing

Units of measurement

°C	degree(s) Celsius
cm	centimetre(s)
gbp	gigabase pair
$GtCO_2$	gigatonne(s) of carbon dioxide
$GtCO_2$-eq	gigatonne(s) of carbon dioxide equivalent
ha	hectare(s)
kg	kilogram(s)
km	kilometre(s)
m	metre(s)
USD	United States dollar(s)

Chemical formulae

CO_2	carbon dioxide

About this publication

This report presents the second global assessment of forest genetic resources (FGR). It builds on the first-ever global FGR assessment, *State of the World's Forest Genetic Resources* (called SoW-FGR1 in this report) (FAO, 2014a), and analyses the progress made in implementing the *Global Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources* (called the Global Plan of Action in this report) (FAO, 2014b) adopted by the FAO Conference in 2013. The present report complements other global assessments prepared under the auspices of the Commission on Genetic Resources for Food and Agriculture (see box), which have focused on the state of genetic resources in various subsectors, as well as on biodiversity for food and agriculture.

The present report also complements two other FAO flagship publications in forestry, the biennial *State of the World's Forests* (SOFO) and the periodic *Global Forest Resources Assessment* (FRA). SOFO presents the status of forests and analyses recent major policy and institutional developments and their impacts on forests and the forest sector. The FRA provides detailed information on various forest-related variables to assist understanding of the global extent of forest resources and their condition, management and use.

The Commission on Genetic Resources for Food and Agriculture

With 179 countries and the European Union as its members, the Commission on Genetic Resources for Food and Agriculture is a unique intergovernmental forum that addresses biodiversity for food and agriculture. The main objective of the Commission is to ensure the sustainable use and conservation of biodiversity for food and agriculture, and the fair and equitable sharing of benefits derived from its use, for present and future generations. The Commission guides the preparation of periodic global assessments of the status of, and trends in, genetic resources and biodiversity for food and agriculture. In response to these assessments, the Commission develops global plans of action, codes of conduct and other policy instruments and monitors their implementation. The Commission raises awareness of the need to conserve and sustainably use biodiversity for food and agriculture and fosters collaboration among countries and other stakeholders to address threats to this biodiversity and promote its sustainable use and conservation.

Scope and content of the report

This report focuses on the genetic resources of trees and other woody plants that are managed or used in forestry (including agroforestry systems) or that could be used for this purpose. These plants may occur in natural and planted forests, as well as in woodlands.

The report has six parts:

- **Part 1 – The contributions of forest genetic resources to sustainable development.** Chapter 1 presents an overview of the value and importance of forests and FGR and discusses the contributions of FGR to the Sustainable Development Goals.
- **Part 2 – State of diversity in forests and other woodlands.** Chapter 2 presents the state of the world's forests, Chapter 3 describes the state of other woodlands, Chapter 4 focuses on the state of diversity of tree and other woody plant species, and Chapter 5 reviews current knowledge on the genetic diversity of these species.

- **Part 3 – State of forest genetic resource conservation.** Chapter 6 and Chapter 7 present the state of *in situ* and *ex situ* FGR conservation, respectively.
- **Part 4 – State of use, development and management of forest genetic resources.** Chapter 8 reports on the state of use of FGR, with an emphasis on forest reproductive material, Chapter 9 presents the state of tree-improvement and -breeding programmes, and Chapter 10 discusses the management of FGR in natural and planted forests and drivers of change affecting FGR management.
- **Part 5 – State of capacities and policies.** Chapter 11 analyses the institutional framework for the conservation, use and development of FGR at the national level and Chapter 12 addresses international and regional cooperation on FGR.
- **Part 6 – Challenges and opportunities.** Chapter 13 presents recommended actions for enhancing FGR management.

The reporting and preparatory process

At its Seventeenth Regular Session in February 2019, the Commission adopted an outline of the present report, as well as reporting guidelines and a preparation timeline (FAO and Commission on Genetic Resources for Food and Agriculture, 2019a). The Commission encouraged countries to initiate collection of information and data for their reports and called on them to submit the reports by 30 June 2020. The outline, the reporting guidelines and the timeline had previously been reviewed by the Intergovernmental Technical Working Group on Forest Genetic Resources (here called the Working Group) at its Fifth Regular Session in 2018.

In June 2019, FAO invited countries to officially nominate national focal points (NFPs) for FGR and to submit their reports to FAO by the agreed date. The reporting guidelines were made available to the nominated NFPs in Arabic, English, French, Russian and Spanish. FAO also invited regional networks on FGR and relevant international organizations to submit reports on their contributions to the implementation of the Global Plan of Action by the same date.

The country reports had two elements: (1) an online questionnaire to gather data and information on FGR; and (2) a complementary written report. The questionnaire was based on the targets, indicators and verifiers for FGR adopted by the Commission at its Sixteenth Regular Session in 2017 for monitoring implementation of the Global Plan of Action. For the written reports, countries were invited to follow the above-presented structure of the global report. Regional networks and international organizations were also invited to submit written reports structured around the four strategic priorities of the Global Plan of Action – (1) improving the availability of, and access to, information on FGR; (2) conservation of FGR (*in situ* and *ex situ*); (3) sustainable use, development and management of FGR; and (4) policies, institutions and capacity building (FAO and Commission on Genetic Resources for Food and Agriculture, 2019b).

In 2019–2020, FAO briefed the regional forestry commissions for Africa, Asia-Pacific, Europe, Latin America and the Caribbean, the Near East, and North America, as well as the Committee on Forestry, on the preparatory process for the report. The Organization also informed the regional FGR networks and its international partners.

The COVID-19 pandemic and related restrictions on meetings and travel hampered countries' efforts to gather data and information from stakeholders involved in FGR activities at the national level. It also created challenges for FAO in organizing regional workshops at which NFPs could discuss the process and clarify the reporting requirements; ultimately, these workshops were conducted virtually, which had the advantage of allowing other national experts (i.e. in addition to NFPs) to attend. Among other things, the workshops involved demonstrations of the use of the online reporting system, the sharing of experiences on the preparation of country reports, and a briefing on the development of a new global information system on FGR. These virtual workshops were convened in Asia (26–27 October 2020), the Southwest Pacific (12–13 November 2020), sub-Saharan Africa (11–12 March 2021), Latin America and the Caribbean (11–12 March 2021), the Near East and North Africa (19–20 April 2021), and Central Asia (22–23 April 2021). In total, they were attended by 96 NFPs and experts from 48 countries.

After the regional workshops, FAO continued to provide (on request) technical support (through remote means such as video calls and emails) to NFPs in finalizing their country reports. FAO also screened the submitted reports for data-entry errors and inconsistencies and, where necessary, contacted NFPs for clarification.

At its Eighteenth Regular Session in 2021, the Commission took note of the progress made in preparing this report and re-invited countries that had not yet done so to nominate their NFPs and alternates, as needed. At the recommendation of the Sixth Session of the Working Group, the Commission also urged countries, regional networks and relevant international organizations that had not yet done so to submit their reports by 31 October 2021 or as soon as possible thereafter.

Several countries submitted their reports long after the new deadline, and FAO continued receiving country reports well into 2024. This created delays and challenges in finalizing the analyses for this report. Nevertheless, a draft of the report was presented to the Seventh Session of the Working Group in March 2023 and then to the Nineteenth Regular Session of the Commission held in July 2023. In July 2024, a second draft of the report was made available for comment by the Commission's Members and observers. The report was then finalized in light of comments received from 15 countries[i] and three international organizations.[ii]

Inputs to the report

As of September 2024, 77 countries had made submissions for this report (see table), representing 77 percent of the global forest area and 43 percent of Commission Members. The online questionnaire was completed by all 77 countries, and nearly half these countries (37) also submitted written reports providing complementary information.

FAO also received reports from two regional networks (the Asia Pacific Forest Genetic Resources Programme – APFORGEN) and the European Forest Genetic Resources Programme – EUFORGEN) and four international organizations or partners – the Alliance of Bioversity International and the Center for International Tropical Agriculture, Botanical Gardens Conservation International, the Royal Botanic Gardens, Kew, and World Agroforestry).

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[i] Argentina, Brazil, Burkina Faso, Canada, Denmark, Finland, Germany, Japan, the Kingdom of the Netherlands, Poland, the Russian Federation, Spain, Sweden, Switzerland and the United States of America.

[ii] Alliance of Bioversity International and the Center for International Tropical Agriculture, the European Forest Institute and World Agroforestry.

TABLE
Countries that made submissions for the present report, by region

Region	Countries
Africa (14 countries)	Burkina Faso (Q), Eswatini (Q), Ethiopia (Q), Guinea (Q,W), Kenya (Q), Madagascar (Q), Mali (Q), Mauritania (Q), Morocco (Q), Namibia (Q), Niger (Q), Nigeria (Q), South Africa (Q), Zimbabwe (Q)
Asia (9 countries)	China (Q,W), India (Q), Indonesia (Q), Japan (Q, W), Lao People's Democratic Republic (Q), Malaysia (Q), Republic of Korea (Q, W), Sri Lanka (Q, W), Thailand (Q, W)
Europe (34 countries)	Armenia (Q), Austria (Q), Belgium (Q), Bulgaria (Q, W), Croatia (Q, W), Cyprus (Q), Czechia (Q, W), Denmark (Q, W), Estonia (Q), Finland (Q, W), France (Q, W), Georgia (Q), Germany (Q, W), Greece (Q, W), Hungary (Q), Iceland (Q, W), Ireland (Q, W), Italy (Q, W), Lithuania (Q, W), Luxembourg (Q), Malta (Q, W), Netherlands (Kingdom of the) (Q, W), Norway (Q, W), Poland (Q,W), Portugal (Q, W), Russian Federation (Q), Serbia (Q, W), Slovenia (Q, W), Spain (Q, W), Sweden (Q, W), Switzerland (Q, W), Türkiye (Q), Ukraine (Q, W), United Kingdom of Great Britain and Northern Ireland (Q, W)
Latin America and the Caribbean (11 countries)	Antigua and Barbuda (Q), Argentina (Q, W), Brazil (Q,W), Chile (Q), Ecuador (Q), El Salvador (Q, W), Guatemala (Q), Mexico (Q), Panama (Q), Peru (Q), Saint Lucia (Q)
Near East (3 countries)	Iran (Islamic Republic of) (Q), Lebanon (Q, W), Yemen (Q)
North America (2 countries)	Canada (Q, W), United States of America (Q, W)
Southwest Pacific (4 countries)	Australia (Q, W), Cook Islands (Q), Fiji (Q), Vanuatu (Q)

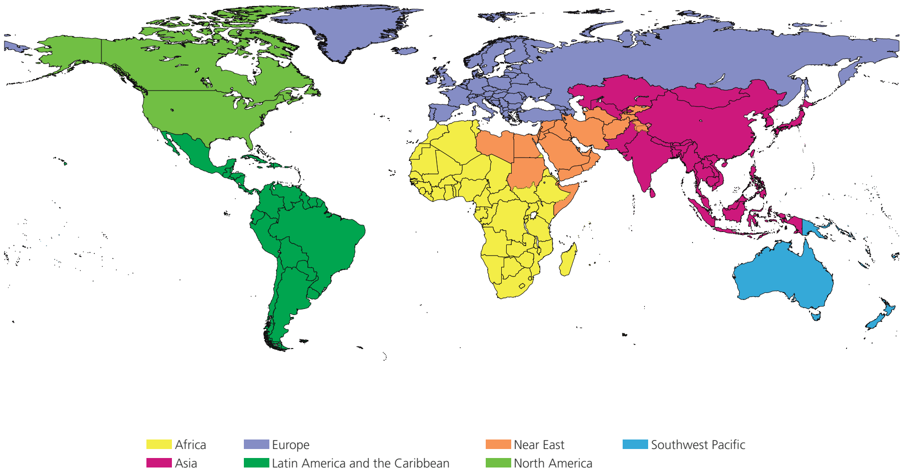
Note: Q = online questionnaire completed; W = written report submitted.

The country reports and the reports submitted by regional networks and international organizations were the main sources of information used in preparing this report. In addition, the report builds on recent scientific literature and relevant earlier FAO and other global assessments. Some chapters draw more heavily than others on other published sources: for example, Chapter 2 is based on the results of FRA 2020 (FAO, 2020), as recommended by the Working Group, to avoid the need for countries to resubmit data they had already provided to FAO for the FRA process (therefore, the questionnaire did not request specific data on forest resources and countries were asked only to provide overviews of their forests in the relevant section of the written reports). Chapter 3 and Chapter 4 of the present report use the findings of earlier assessments on woodlands and taxonomy of trees and other woody plants, respectively, as the main sources of information. Countries were not expected to carry out detailed inventories of woodlands or species for this report but, rather, to summarize existing knowledge based on the data they had provided to the FRA and to global taxonomic assessments.

The country data and written reports, and the reports by regional networks and international organizations, will be made available through a new global information system on FGR developed by FAO.

FIGURE

Assignment of countries to regions in this report



Notes: Refer to the disclaimer on page ii for the names and boundaries used in this map. Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties. Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined.

Regional classification of countries

The assignment of countries to regions in this report is based on FAO's seven regional groupings – Africa, Asia, Europe, Latin America and the Caribbean, the Near East, North America and the Southwest Pacific – used for election and statistical purposes (see figure). The regional assignment of Commission Members also follows this grouping.

Executive summary

People use trees and other woody plants (i.e. shrubs, bamboos and rattans) for multiple purposes and manage them in a broad range of production systems, including natural forests and woodlands. The genetic resources of these species underpin the sustainable supply of diverse products and make essential contributions to food security, livelihoods and ecosystem services. Moreover, the genetic diversity of trees and other woody plants is crucial for maintaining the resilience of forests and enabling their adaptation to climate change.

This report presents the second global assessment of forest genetic resources (FGR), defined as the heritable materials maintained within and among trees and other woody plants that are of actual or potential economic, environmental, scientific or societal value. The report builds on the first global assessment of FGR, published by FAO in 2014 as *The State of the World's Forest Genetic Resources* (hereafter referred to as SoW-FGR1). It analyses the progress made in implementing the *Global Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources* ("Global Plan of Action") adopted by the FAO Conference in 2013. It draws on information provided by 77 countries that, combined, represent 77 percent of the global forest area, as well as inputs from two regional networks on FGR and four organizations; recent scientific literature; and previous relevant global assessments.

Forest genetic resources are neglected in the context of sustainable development, biodiversity, climate change and sustainable forest management. Global awareness of the importance of FGR is low, although the country reports provide many examples of how the conservation, use and development of FGR have contributed to countries' efforts to pursue sustainable development. Many countries also reported that FGR have crucial roles to play in the adaptation of forests to climate change, safeguarding biodiversity, improving productivity and developing new products. The Kunming–Montreal Global Biodiversity Framework offers an opportunity to raise global awareness of the importance of genetic diversity among all species, including forest trees and other woody plants, and to mobilize support for the implementation of the Global Plan of Action.

The availability of information on forest genetic resources has increased in the last decade but remains inadequate, hindering efforts to improve their management. In their reports, countries provided data on more than 2 800 species of trees and other woody plants. Sixty-four percent of the 77 reporting countries indicated that they have national FGR inventories, and 55 percent also have national FGR information systems. The most common areas of work documented by inventories are FGR conservation, followed by research and development and the production of forest reproductive material. Information on FGR is still scattered at the national level, however, and existing FGR inventories often struggle to connect multiple data sources maintained by different stakeholders to gain a comprehensive picture of the status of FGR.

Several international organizations have created databases that make available valuable information and knowledge on various aspects of FGR, but many countries are unaware of these. Thus, there is a need to promote the available sources of information and knowledge on FGR to enhance FGR work.

Forests cover nearly one-third of the world's forest area, but deforestation continues, especially in the tropics. The global forest area was about 4.06 billion ha (31 percent of the total land area) in 2020. Nearly half (45 percent) of the world's forests are in the tropical biome, followed by the boreal (27 percent), temperate (16 percent) and subtropical (11 percent) biomes. Naturally regenerating forests comprise 93 percent (3.75 billion ha) of the global forest area and planted forests 7 percent (294 million ha). Despite global efforts to halt deforestation and increase forest cover, the global forest area decreased by 178 million ha between 1990 and 2020 and by 4.74 million ha per year between 2010 and 2020. The biggest annual decrease in forest area in that period was in Africa (3.67 million ha), followed by Latin America and the Caribbean (2.81 million ha). On the other hand, forest area increased between 2010 and 2020 in Asia (by 1.03 million ha per year), followed by Europe (470 000 ha per year). More than 90 percent of global deforestation in 2000–2018 took place in tropical forests, and nearly 90 percent of deforestation was due to agricultural expansion. Globally, the main management objective is the production of wood and non-wood forest products (accounting for 31 percent of the global forest area), followed by multiple use (22 percent), the protection of soil and water (12 percent) and biodiversity conservation (11 percent).

Trees and other woody plants are also found outside forests in woodlands and agroforests, which cover about one-fifth of the world's land area. The global extent of other wooded land (OWL) was reported at 977 million ha in 2020, although remote sensing suggests a much larger area (1.7 billion ha), indicating significant gaps in national reporting. The global area of OWL was reported to decline by 31 million ha between 1990 and 2020. Agroforests, which are rarely inventoried systematically, also cover large areas, with estimates indicating that up to 1.11 billion ha of croplands and grasslands globally have more than 10 percent tree cover. Combined, OWLs and agroforests could cover about 2.7 billion ha, which is close to 20 percent of the global land area. Studies have indicated substantial tree species diversity in woodlands, although data coverage is patchy, and agroforestry systems harbour varied tree species diversity, from one to several hundred species. Strengthening global reporting, integrating agroforestry into sustainable land-use strategies, and involving local communities in land management are crucial for ensuring the long-term viability of these vital landscapes and the FGR they harbour.

Taxonomic and threat assessments carried out in the last decade have increased information on the status of trees and other woody plants: nearly one-third of tree species are threatened, and the majority of tree species are single-country endemics. The number of named species is estimated at nearly 58 000 for trees, 1600 for woody bamboos and about 500 for rattans. Specific uses by people have been documented for about one-quarter of tree species, 12 percent of bamboos and nearly a third of rattans. Trees occur in nearly all parts of the world, but the diversity of species is concentrated in the tropical and subtropical forest biomes. Of all known tree species, 58 percent are endemic – occurring naturally in only one country – and the natural distribution ranges of most others are limited to given regions and habitats. About 30 percent of all tree species are threatened; most occur in the tropics and subtropics. Two-thirds of bamboos occur naturally in the tropical zones and the remainder occur in the temperate zone. Relatively few bamboo species are common and widespread and most are rare, but no comprehensive threat assessment has been carried out. All rattans occur in the tropics and 12 species are threatened but less than 10 percent have been assessed for their threat status. In the tropical and subtropical forest biomes, the main threats to trees and other woody plants arise from unsustainable harvesting and the conversion of forests to agriculture; in boreal and temperate forests, invasive species, insect pests and diseases threaten some species. Climate change is creating challenges for trees and other woody plants in all forest biomes and exacerbating damage caused by fire, insect pests and diseases. Infrastructure development is another common threat in most regions.

The loss of genetic diversity in trees and other woody plants continues, especially in the tropics and subtropics. Genetic diversity has been characterized for 1 661 species of trees and other woody plants based on non-molecular information (typically obtained from provenance trials) and for 750 species based on molecular information (e.g. range-wide sampling of populations for molecular marker studies). The number of unique species characterized based on molecular and/or non-molecular information totals 1 784. Many studies have been carried out in different parts of the world to characterize genetic diversity with molecular techniques, but few of these have assessed changes in genetic diversity over time. Some countries have established genetic monitoring systems for tracking temporal change, but such systems are in their infancy. There is evidence that genetic diversity remains high in common and widely distributed species but that rare and threatened species have lost significant amounts of genetic diversity (nearly 40 percent, in one case). Many species in the boreal and temperate forest biomes have large distribution ranges and population sizes and maintain high genetic diversity. Species in the tropical and subtropical forest biomes tend to have limited distribution ranges and small population sizes, making them more vulnerable to genetic erosion. Globally, deforestation, forest degradation, fire, pests, diseases and invasive species pose threats to many trees and other woody plants and are eroding their genetic diversity.

The number of species targeted by *in situ* forest genetic resources conservation programmes increased in the last decade, but these programmes include only 2 percent of all named species. *In situ* conservation is the preferred approach for conserving the FGR of trees and other woody plants because it maintains evolutionary processes within populations. It is also intrinsically dynamic because it enables temporal and spatial changes in genetic diversity; moreover, it does not exclude the use of FGR by people, provided that the regeneration and continued evolution of species are not jeopardized. Of the reporting countries, 83 percent indicated that they have national *in situ* conservation programmes in place. The most common components of these programmes are protected areas (indicated by 70 percent of reporting countries) and *in situ* conservation units (68 percent), followed by production forests (53 percent). A few countries (5 percent) also use other components, such as permanent monitoring or research plots and sacred forests. The number of species included in conservation programmes increased from nearly 1 000 (including subspecies) in SoW-FGR1 to 1 387 species (2 percent of all named species) in the present report. The number of species in these programmes was highest in Latin America and the Caribbean (576), followed by Asia (336), Europe (207) and Africa (158). Globally, countries reported 35 114 conservation units of FGR covering 533 million ha.

Recent studies have shown that numerous populations of socioeconomically important trees prioritized for *in situ* conservation are located outside existing protected areas and that a large proportion of tree species receives only limited protection in protected areas. This points to the importance of designing *in situ* conservation programmes with multiple components, which could include forest patches in agricultural landscapes. Climate change is expected to increase the need for active management measures to ensure that conserved populations of trees and other woody plants maintain their vitality and regeneration capacity; this may include translocating conservation populations to new sites where future climatic conditions are projected to be more favourable.

***Ex situ* conservation is a crucial complement of *in situ* conservation, and it is also important for the supply of germplasm for restoration efforts.** The aim of *ex situ* FGR conservation is to maintain representative samples of species' genetic diversity, not only for conservation purposes but also for reforestation and tree breeding. *Ex situ* conservation does not allow the ongoing evolution of species and is therefore a static approach; nevertheless, it is an important backup measure for *in situ* conservation, especially when populations in natural habitats are small. Of the reporting countries, 75 percent indicated that they have national *ex situ* conservation programmes in place. The most common component of these programmes is storage facilities for seeds, pollen and other tissues (reported by 64 percent of countries), *ex situ* conservation stands (62 percent), and field collections (61 percent). Tree-seed centres (or tree gene banks), which typically operate separately from crop gene banks, are the most important storage facilities. About 10 percent of submitting countries also reported other components, such as arboreta, botanic gardens and DNA banks.

Globally, there are about 296 000 accessions in seed banks and field collections, which is almost double the number reported in SoW-FGR1 (nearly 160 000 accessions). Countries also indicated the existence of more than 14 000 *ex situ* conservation stands covering about 179 000 ha. The reported *ex situ* conservation programmes include nearly 1 100 species (less than 2 percent of all species). The number of species in *ex situ* programmes was highest in Asia (401 species), followed by Latin America and the Caribbean (293), North America (202) and Europe (167). The number of species conserved *ex situ* is considerably lower than reported in SoW-FGR1 (i.e. 1 800 species and subspecies). The extent to which this finding reflects an actual decrease in the number of targeted species is unclear because it could be because fewer countries provided information on this aspect for the present report; moreover, they were asked to report only on species (i.e. not including subspecies). It is also possible that some countries incompletely documented the *ex situ* conservation efforts of certain stakeholders.

Research on *ex situ* conservation methods maintained the momentum indicated in SoW-FGR1, with knowledge increasing on the seed biology and storage behaviour of forest trees, among other aspects. The seed biology of boreal and temperate species is better known than that of tropical species, which more commonly have recalcitrant seeds (i.e. are sensitive to desiccation).

Many countries are experiencing persistent or periodic shortages of forest reproductive material, which poses a challenge for achieving the target of a 3 percent increase in the global forest area by 2030 and other global commitments on forests, biodiversity and climate. The demand for forest reproductive material is strong worldwide, but progress in reinforcing national tree-seed programmes has been modest in the last decade. Of those countries that made submissions for the present report, 70 percent have such programmes, and some other countries produce forest reproductive material through multiple initiatives that lack national-level coordination and oversight. Sixty percent of reporting countries indicated that they have extension programmes to promote FGR use. Globally, countries reported a total of 876 species for which reproductive material is produced. There are nearly 83 000 seed stands covering about 7 million ha and more than 5 800 seed orchards covering nearly 39 000 ha. More than 3.1 billion plants are produced annually through macro- and micropropagation, although this figure is likely an underestimate because many countries with large areas of planted forests did not report their annual plant production. The number of seedlings planted per year varies considerably between countries (from well below 1 million to 15 billion).

The use of unimproved germplasm continues to play a major role in forestry. In many countries, the quantity of forest reproductive material is limited and its quality low, and demand is not being met. Climate change is affecting both the production and deployment of forest genetic material, creating additional complexity in the use of FGR. Several countries reported that they are meeting shortages in domestic production with imports of seeds or seedlings, but such imports typically account for only a small proportion of overall demand. Few countries can certify forest reproductive material for international trade, which limits the potential role of imports. Both developed and developing countries reported having limited financial and human resources for their tree-seed programmes. This poses a significant challenge for global efforts to improve people’s livelihoods by establishing new forests to produce wood and non-wood forest products, conserve biodiversity and mitigate climate change.

Some countries raised concerns about the effects of climate change on the production of forest reproductive material, with stressed trees likely to produce fewer seeds. Conversely, some countries indicated that seed maturation could benefit from increased temperatures and changed precipitation patterns in some regions. Few countries, however, have fully evaluated the impacts of climate change on seed production and harvesting. Because climate change is expected to alter the flowering patterns of trees and the timing of seed maturation, several countries indicated that they are prepared for additional challenges in organizing seed collection from both seed stands and seed orchards. Many countries noted challenges in establishing new seed orchards to replace ageing ones.

Tree-improvement and -breeding programmes focus on only 1 percent of species and, for most of those, efforts have not advanced beyond first-generation selection. Tree-improvement and -breeding programmes are ongoing in all regions, albeit at differing levels of intensity and investment. Seventy-five percent of reporting countries indicated that they have such programmes. The main stakeholder groups with tree-breeding programmes are public entities (in 70 percent of reporting countries), private companies (44 percent) and public–private partnerships (30 percent). Sixteen percent of countries reported that other stakeholders – such as registered charities and non-profit associations – are also operating tree-breeding programmes. Globally, nearly 500 species are subject to tree-breeding programmes. The number of species in these programmes is highest in Asia (185), followed by Europe (112), Latin America and the Caribbean (108), and Africa (86).

SoW-FGR1 reported more species and subspecies (730) in tree-breeding programmes. It is probable, however, that the actual number of species has not changed significantly in the last decade, with the difference likely explained by the smaller number of reporting countries for the present report and because countries were asked to report only on species (i.e. not subspecies). For 60 percent of the reported species, first-generation selection represents the most advanced material deployed for production; a further 13 percent of the species in first-generation seed orchards have been culled based on progeny tests. About 5 percent of species are subject to fourth-generation selection (the most advanced material deployed), as reported by 8 percent of the countries. Hybrid breeding is also a widely applied approach, with a total of 34 hybrids reported globally. Thirty percent of reporting countries use marker-assisted selection tools in tree-breeding research, and 19 percent indicated that genomic technologies are being used. Genetically modified transformants have been developed for more than 30 tree species, but their use in practical forestry is limited. Several countries are using gene-editing technology to study gene functions in forest trees and to explore how research results could be used to accelerate tree breeding. Nevertheless, the application of gene editing in tree breeding is still in its early stages.

Genetic aspects need to be better incorporated into the management of natural and planted forests. Paying attention to genetic aspects is crucial for sustainable forest management and for maintaining the adaptability, resilience and vitality of natural and planted forests. The country reports show that forest managers and policymakers tend to overlook genetic aspects, however, and, when they do consider them, they do so more frequently for planted forests. Natural forests are commonly assumed to have ample genetic diversity, although their history is often poorly documented. Deforestation and forest fragmentation have slowed at the global scale, and harvesting in many parts of the world has become less destructive. Nevertheless, many tree species and their populations are genetically impoverished, especially in the tropics, and recovery is slow.

Many countries indicated that the most damaging drivers of change are climate change, including an increased frequency of related disasters (e.g. drought, fire, storms and outbreaks of diseases and insect pests), and invasive species, creating considerable challenges for FGR management. On the positive side, some countries reported increased recognition among forest managers and policymakers that genetic diversity is essential for the adaptation of forests to climate change and for coping with outbreaks of pests and diseases. The country reports also provided examples of efforts to increase species and genetic diversity in natural and planted forests and in the restoration of degraded forests.

The full integration of genetic aspects into forest management requires improvement in approaches for collecting information on FGR as part of regular forest inventories. Methodologies for using FGR data in forest management planning should also be further developed. The use of existing and emerging technologies should be enhanced as a means for improving FGR management.

Several countries have made progress in strengthening their institutional frameworks for forest genetic resource conservation, sustainable use and development but, globally, considerable limitations and gaps exist, especially in terms of human and financial resources. Among the reporting countries, 52 percent indicated that they have national coordination mechanisms for FGR such as national committees or working groups. These mechanisms are dominated by governmental and research organizations, and participation by farmers, forest owners, the private sector and non-governmental organizations is less common. About 58 percent of reporting countries have developed national FGR strategies, but these tend to be focused on FGR conservation and to give less attention to FGR use and development. The integration of FGR into other relevant national policies is inadequate. For example, 66 percent and 48 percent of reporting countries, respectively, indicated that they had integrated FGR into national forest policies and national adaptation strategies; 74 percent reported that FGR is considered in national biodiversity strategies and action plans.

Countries have made relatively little progress in strengthening human capacity for managing FGR, and some countries noted that their human resources have declined since SoW-FGR1. FGR are seldom well covered by technical and vocational forestry education, and very few countries have academic FGR-related education programmes. Many countries also reported struggling to mobilize the necessary financial resources for work on FGR.

International and regional cooperation on forest genetic resources is indispensable for the implementation of the Global Plan of Action and needs to be reinforced. International and regional cooperation on FGR is crucial because the distribution ranges of many trees and other woody plants extend across countries and even regions, and many threats to FGR do not respect political borders. Countries benefit from international and regional cooperation in many ways. For example, it enables them to share information, experiences and knowledge on FGR management, increase the efficiency of FGR work, share costs, and avoid duplication of effort. Of the reporting countries, 69 percent indicated that they participate in international collaboration on FGR-related research and development, and 70 percent reported that they are involved in regional FGR networks. Several countries noted that a lack of financial and human resources and research infrastructure impedes their involvement in international and regional cooperation.

The Global Plan of Action is highly relevant to the needs and priorities reported by countries. Progress has been made in implementing the Global Plan of Action at the national, regional and global levels, but limitations and gaps exist that require continued and reinforced action. The four priority areas identified in the Global Plan of Action – (1) improving the availability of, and access to, information on FGR; (2) conservation of FGR (*in situ* and *ex situ*); (3) sustainable use, development and management of FGR; and (4) policies, institutions and capacity building – are still relevant. Thus, the actions proposed in the present report reflect, in a concise form, the 27 priorities indicated in the Global Plan of Action.

FGR underpins the many contributions of forests and trees to sustainable development and their benefits for people, biodiversity and the climate. It is important, therefore, to increase international awareness of the Global Plan of Action and the need for its full implementation.

Part 1

THE CONTRIBUTIONS OF FOREST GENETIC RESOURCES TO SUSTAINABLE DEVELOPMENT

Chapter 1

The value and importance of forest genetic resources

1.1 Introduction

People use trees and other woody plants (i.e. shrubs, bamboos and rattans) for multiple purposes and manage them in a broad range of production systems, including natural forests and woodlands. The genetic resources of these species underpin the sustainable supply of diverse products and make essential contributions to food security, livelihoods and ecosystem services. Moreover, the genetic diversity of tree and other woody plant species is crucial for maintaining the resilience of forests and enabling their adaptation to climate change.

The term "forest genetic resources" (FGR) refers to the heritable materials maintained within and among tree and other woody plant species that are of actual or potential economic, environmental, scientific or societal value, as defined in the first *State of the World's Forest Genetic Resources* report (called here SoW-FGR1; FAO, 2014a). SoW-FGR1 considered FGR as a subset of plant genetic resources for food and agriculture (PGRFA) – that is, any genetic material of plant origin of actual or potential value for food and agriculture (FAO, 2009a). Although the two definitions overlap, FGR and PGRFA can be differentiated by the management context in which people use these resources (e.g. forestry versus crop production). Moreover, tree and other woody plant species typically have multiple uses, ranging from construction materials, food (for livestock and people), fuels and medicines to environmental and social uses (see Diazgranados *et al*., 2020), while most agricultural crops have only one specific use (typically food). For the preparation of this report (similarly to SoW-FGR1), countries were invited to report on tree and other wood plant species managed in the forestry context (including agroforestry).

Given the vast number of tree and other woody plant species and limited financial and human resources, most countries need to prioritize species for FGR conservation and management based on needs, the availability of resources, and the threat posed. SoW-FGR1 found that economic value and conservation status are the main reasons for priority-setting, followed by environmental and sociocultural values (FAO, 2014a). It also demonstrated the contributions of FGR to sustainable development and noted that a lack of national policies and action on FGR stems from insufficient awareness of the importance of FGR for humankind and more generally for life on Earth.

Based on the findings of SoW-FGR1, the Commission on Genetic Resources for Food and Agriculture (Commission) agreed on the *Global Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources* (referred to hereafter as the Global Plan of Action), which was adopted by the FAO Conference in 2013 (FAO, 2014b). The Global Plan of Action identifies 27 strategic priorities grouped into four priority areas: 1) improving the availability of, and access to, information on FGR; 2) the conservation of FGR (*in situ* and *ex situ*); 3) the sustainable use, development and management of FGR; and 4) policies, institutions and capacity building. Despite certain differences in the reporting guidelines between the first and second reports, the present report assesses the progress made in improving the management of FGR since SoW-FGR1 was published in 2014.

This chapter provides an overview of the importance of FGR and their contributions to people's livelihoods and well-being and to sustainable development. Based on country reports,[1] it also presents a summary of what countries consider to be the main contributions of FGR. The chapter does not re-analyse the role of forests, trees and FGR in providing ecosystem services, which was discussed in detail in SoW-FGR1. The importance of biodiversity for food and agriculture, including FGR, in providing ecosystem services was also analysed in another Commission assessment (FAO, 2019a). Other comprehensive global assessments on ecosystem services (TEEB, 2018; IPBES, 2019) have also been published recently.

1.2 The importance of forests and trees for people, biodiversity and climate

Trees are the foundation species of forest ecosystems, which occur in each of the world's four major climatic domains (boreal, temperate, subtropical and tropical) and cover 31 percent of the global land area (FAO, 2020). Trees and other woody plants are also important components of other wooded land, which cover 7 percent of the land area (FAO, 2020), and of agricultural landscapes. More than 80 percent of the world's forest area is found in patches larger than 1 million ha, concentrated in a few locations mostly in the boreal coniferous and tropical rainforest zones (FAO and UNEP, 2020). The remainder of the world's forests are scattered and comparatively small in area; many are highly valuable and accessible. A global study of the spatial relationships between people and forests found that 75 percent of all people outside urban areas (that is, 3.27 billion people) lived within 1 km of a forest in 2019 (Newton *et al*., 2022).

The potential for people to use a forest for their own benefit depends (in addition to having physical proximity to the forest) on their rights to manage it or extract wood and non-wood products from it. An estimated 73 percent of forests was publicly owned in 2015 and 22 percent was under private ownership (FAO, 2020). In recent decades, governments have increasingly granted management rights to local communities and Indigenous Peoples and to business entities and institutions; globally, however, public administrations still held the management rights to 83 percent of publicly owned forests in 2015 (FAO, 2020). It has been reported that Indigenous Peoples and local communities were recognized legally as owning at least 447 million ha (12 percent of the total forest area) and holding rights to more than 80 million ha (2 percent of the global forest area) in 2017 (RRI, 2018).

For most forest owners and managers, wood is by far the most economically important forest product, but forests and trees are also sources of food, fodder, fuel and other products that can be harvested and consumed at home or sold and thereby contribute to food security and livelihoods across seasons and years, even in difficult times (FAO, 2022a). At least 3.5 billion people use non-wood forest products (NWFPs) (Shackleton and de Vos, 2022), and about 2.6 billion people rely on wood and other traditional fuels for household cooking (IEA *et al*., 2021). Angelsen *et al.* (2018) found that forests contributed 20–25 percent of the household incomes of forest-adjacent communities in 24 tropical countries surveyed in Africa, Asia and Latin America. A global comparative analysis showed that 77 percent of surveyed rural households were engaged in wild-food collection (Hickey *et al*., 2016). The subsistence use of forests and woodlands can thus be far more important for the livelihoods and well-being of

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[1] In this publication, a "country report" comprises the data and written report on FGR submitted by a country to FAO for preparation of *The Second Report on the State of the World's Forest Genetic Resources.*

Oak logs harvested in Germany

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people than the forest products traded in local or international markets.

Wood-based goods from forests are well-captured by forest product statistics because of their economic importance and well-established markets. In 2020, the export value of all wood-based forest products amounted to USD 226 billion (FAO, 2022b); in 2015, the formal forest sector (i.e. the wood-based industry) directly contributed more than USD 663 billion to the world's gross domestic production (GDP) (Li *et al*., 2022). Taking into account all economic effects (i.e. direct, indirect and induced economic contributions), the forest sector contributed more than USD 1.52 trillion to national economies in 2015 (Li *et al*., 2022). The average annual number of people employed in the forest sector was approximately 33 million in 2017–2019 (Lippe *et al*., 2022).

Several NWFPs also have significant local, national and international markets. In 2011, total income from the production of NWFPs was estimated at about USD 88 billion, of which most (USD 77 billion) resulted from the production of plant-based NWFPs (FAO, 2014). This is likely to underestimate the actual global income generated by NWFP production because of difficulties in the international classification of NWFPs and related data collection (Sorrenti, 2017; Muir *et al*., 2020). A recent study of 28 European countries found that the total value of NWFPs collected per year amounts to 71 percent of the value of annual roundwood production (Lovrić *et al*., 2020).

In addition to providing huge benefits for people in the form of wood and non-wood products, forests play crucial roles in maintaining biodiversity (FAO and UNEP, 2020) and providing other ecosystem services (MEA, 2005). Most of the world's forested areas are hotspots of both local (alpha) and regional (gamma) diversity of vascular plant species (Sabatini *et al*., 2022; Brummitt, Araújo and Harris, 2021). In addition, forests provide habitats for around 80 percent of amphibian species, 75 percent of birds and 68 percent of mammals (Vié, Hilton-Taylor and Stuart, 2009). Many other species, such as invertebrates (mostly insects) and fungi, also depend on forests (FAO and UNEP, 2020). Mangrove forests support aquatic biodiversity and fisheries by providing habitats, spawning grounds and nurseries for numerous fish and shellfish species (FAO, 2023a) and by trapping sediments that might otherwise adversely affect seagrass beds and coral reefs (FAO and UNEP, 2020).

Forests and their biodiversity make significant contributions to agricultural production. Pollination services, for example, are an important benefit of forest biodiversity for crop production. Both large contiguous and small remnant forests provide pollinators with nests and forage, thereby enhancing pollination on nearby agricultural lands (Krishnan *et al*., 2020). It has been estimated that more than 70 percent of the world's food crops depend, at least in part, on pollinators for sustained production, yield and quality (Klein *et al*., 2007). Farming systems with the long-term presence of trees also have the potential to maintain rich pollinator communities (IPBES, 2016). Forests also support agricultural production by generating rainfall (Wright *et al*., 2017; Smith, Baker and Spracklen, 2023) and moderating temperatures (Alkama and Cescatti, 2016) over large geographical areas. Forested watersheds supply three-quarters of the world's accessible freshwater (MEA, 2005).

Forests play an important climatic role by absorbing atmospheric carbon dioxide (CO_2) and storing large amounts of carbon in their vegetation and soils. According to the Intergovernmental Panel on Climate Change, global net anthropogenic greenhouse-gas emissions increased by 12 percent between 2010 and 2019, amounting to 59 $GtCO_2$-eq, of which 22 percent (13 $GtCO_2$-eq) came from agriculture, forestry and other land uses (AFOLU) (IPCC, 2023). Half the AFOLU emissions were from agriculture and the other half were predominantly from deforestation (IPCC, 2023). Despite these emissions, land ecosystems still constituted a net sink of CO_2, removing 6.6 $GtCO_2$ from the atmosphere per year in 2010–2019 (IPCC, 2023).

Forests and trees offer multiple mitigation and adaptation opportunities that can simultaneously benefit people, biodiversity and climate, although they cannot fully compensate for delayed mitigation actions in other sectors (IPCC, 2023). These benefits are weakened by continued deforestation, however, which is due mostly to the conversion of forests to crop fields and pastures (FAO, 2022c).

1.3 Economic, social, cultural and environmental benefits of forest genetic resources

It has been estimated that more than 34 000 tree and other woody plant species (including tree crops) worldwide are of socioeconomic, environmental and scientific importance (FAO, 2014a). Of these species, 98.5 percent are angiosperms (including bamboos and palms) and 1.5 percent are gymnosperms (excluding cycads). Only about 2 400 species are managed actively in forestry for products or services (FAO, 2014a); by one estimate, nearly 1 600 species are traded internationally for timber (Mark *et al*., 2014). Globally, most species managed in forestry are harvested from natural or semi-natural populations, but a relatively small number of species, such as acacias (*Acacia* spp.), neem (*Azadirachta indica*), coastal she-oak (*Casuarina equisetifolia*), eucalypts (*Eucalyptus* spp.), pines (*Pinus* spp.) and teak (*Tectona grandis*), are planted widely outside their natural distributions. For the present report, countries reported (in total) more than 2 800 species and provided detailed data on FGR management.

SoW-FGR1 reviewed the multiple benefits of FGR and concluded that the specific economic value of FGR is difficult to isolate from the economic benefits provided by forests and trees, even for wood products (FAO, 2014a). The country reports submitted for the preparation of this second global report confirm that most, if not all, reporting countries consider that the importance of FGR is based on the many products and services provided by forests and trees. Although most reports stressed the importance of economic, social, cultural and environmental benefits of FGR, several also highlighted the option values offered by FGR for the continued adaptation of forests to climate change, pests and diseases and for the future development of new forest-based products.

For most reporting countries, the contribution of the formal forest sector to GDP is typically modest, at 1–2 percent. This percentage generally only captures those forest products with well-established markets, and few countries reported the value of the other benefits of forests and trees. An exception was Brazil, which provided information demonstrating that NWFPs and ecosystem services (e.g. biodiversity conservation, carbon storage, regulation of the hydrological cycle and erosion control) provide significant benefits to people and the national economy. Brazil estimated that the overall forest-based sector (including NWFPs and ecosystem services in both natural and planted forests) contributes 4 percent of GDP and generates 6 million jobs; in comparison, the wood-based forest sector accounts for 1.2 percent of GDP and employs 3.75 million Brazilians. These estimates highlight the economic importance of NWFPs and ecosystem services in addition to the formal forest sector. According to Brazil's country report, the most economically and socially important NWFPs are açaí (*Euterpe oleracea*) (mainly berries but also used as a vegetable – palm heart), araucaria nuts (*Araucaria angustifolia*), Brazil nuts (*Bertholletia excelsa*), cashew nuts (*Anacardium occidentale*), rubber (*Hevea brasiliensis*), yerba mate (*Ilex paraguariensis*) and resin (*Pinus* spp.). In total, Brazil reported on 476 species and emphasized the opportunities arising from the domestication and use of native tree species for bioeconomy, technological innovation, and human health and nutrition.

Several other countries highlighted the economic importance of NWFPs and the opportunities offered by FGR for developing

Harvesting Brazil nuts (*Bertholletia excelsa*)

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new products. Australia reported that the total value added by its forest sector was USD 6.2 billion in 2018–19, which was 0.5 percent of the national GDP. Although the majority of about 200 commercially important tree species in Australia are used for wood production, several species are also grown for NWFPs, such as oil (tea tree, *Melaleuca alternifolia*) and nuts (macadamia, *Macadamia integrifolia* and *M. tetraphylla*). Originally harvested in natural forests, tea tree is now grown in plantations covering 4 500 ha in New South Wales and Queensland. The tea-tree industry, which exports more than 90 percent of the oil produced, contributed around USD 27 million (farm-gate value) to the economy in 2018. The endangered macadamia species, which are native to subtropical rainforests in New South Wales and Queensland, are also grown in plantations totalling 33 000 ha, producing around 50 000 tonnes of nuts-in-shell annually, with a value of USD 179 million (at the farm gate).

Australia reported that several other tree and woody plant species are cultivated for food, fodder, medicine and traditional use by Indigenous Peoples. It also noted that several Australian tree species have been analysed for their anticarcinogenic, anti-inflammatory, anti-obesity, antimicrobial, cosmetic and food-preservative properties. It is likely that many more tree species are potential sources of new products because only a small proportion (estimated at 5–10 percent) of approximately 2 500 native tree species in Australia have been studied for their commercial potential.

In Canada, the forest sector directly accounted for USD 24 billion (about 1.2 percent of GDP) in 2022, with 75 species reported. The country report noted that this share of GDP does not adequately reflect the importance of the forest sector, which creates more jobs and contributes more to the balance of trade than do other major sectors. Moreover, the forest sector has a specific value in rural areas and remote communities, providing employment for over 212 000 people and revenue for about 300 municipalities across the country. Although the main economic role of forests in Canada is the supply of wood products, the annual value of the two major NWFPs, maple syrup and Christmas trees, is also significant, at about USD 300 million and USD 66 million, respectively.

The forest industry is actively developing new ways to use forests to add value to the Canadian economy and offset greenhouse-gas emissions. One product with strong potential is transparent wood made from modified lignin – it is stronger than glass and has a higher insulation factor. Canada's forests are the country's second-largest source of renewable energy after hydroelectricity; forest biomass was the source of 85 percent of Canada's bioenergy in 2016.

The formal forest sector does not play a significant role in the national economies of all reporting countries, and other benefits derived from forests and trees can override the ones provided by commercial wood or NWFP production. For example, the economic importance of forests is low in Denmark, and primary forest products provide only a marginal contribution to the country's GDP (the country's wood-based industries rely largely on imported wood). The environmental and recreational values of forests are considered far more important, and forest owners gain a significant proportion of their earnings from secondary activities such as hunting rights leases and house and land rentals. The Kingdom of the Netherlands reported that the forest sector plays only a modest role in the country's economy and that up to 90 percent of the wood used is imported. Nevertheless, Danish and Dutch forests are highly appreciated by the public for their environmental and social values, and many tree species are conserved for their genetic resources. FGR conservation strategies encompass 81 species in Denmark and 63 species in the Netherlands.

Commercial wood harvesting for timber is prohibited in some countries. In Lebanon, for example, which reported on 54 species, wood is used mainly by rural communities as fuel and for producing charcoal. In addition, many rural people gather NWFPs for additional income, such as pine nuts (*Pinus pinea*) and carob pods

(*Ceratonia siliqua*). Many tree and scrub species are also used in Lebanon for medicinal and aromatic purposes, with an estimated annual market value of USD 18.6 million. In Sri Lanka, which listed 32 species in its report, a logging ban was imposed in 1990 to halt commercial wood harvesting in natural forests, but both natural and planted forests continue to supply NWFPs and woodfuel. Approximately three-quarters of the country's population in the country's dry and wet zones still depend on natural forests for woodfuel and other forms of biomass for their household cooking. In the dry and intermediate zones, 40 percent of rural people depend on forests for fuel, wood, NWFPs and grazing land.

The country reports contain many examples of how the use and development of FGR have contributed to increasing the economic and other benefits of forests to people and to sustainable development in general. Argentina's report, for example, noted that the introduction of tree species (e.g. *Eucalyptus*, *Pinus* and *Salix* ssp.) from other countries for forestry and integration into agricultural and livestock systems has led to the development of numerous tree-breeding programmes in the country. This, in turn, has brought fast-growing tree germplasm with remarkable wood quality into production and generated interest and similar efforts for native tree species. FGR work in Argentina currently involves 129 species.

China reported that the country's tree improvement and breeding work has contributed significantly to increasing wood supply, which is considered the main contribution of forests to sustainable development. Commercial timber production in China reached about 100 million m^3 in 2019, representing an increase of 23 percent over 2012. Improved tree germplasm has also been made available for producing NWFPs – more than 100 tree and woody plant species are cultivated in China for food and edible oils. For example, tea-oil camellia (*Camellia oleifera*) is cultivated on 4.5 million ha, with an estimated economic value of the extracted oil of USD 5.6 billion in 2018. China, which reported 323 species, noted that the use of FGR has made important contributions to socioeconomic development, food security and poverty alleviation.

Finland provides another example of the role of FGR in increasing wood production. The country reported that the use of genetically improved germplasm in forest regeneration for the three major wood-producing species, Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and birch (*Betula* spp.), has contributed significantly to the 40 percent increase in the growing stock achieved over the last 50 years. The forest sector also plays a significant role in the Finnish economy, generating 4.5 percent (about USD 8.5 billion) of GDP and directly employing more than 62 000 people in 2018. Wood is used extensively to increase self-sufficiency in energy production and reduce the use of fossil fuels. Wood-based fuels account for about 25 percent of total energy consumption in Finland and for more than 83 percent of all renewable energy sources in 2019. Finland noted in its report that adaptation to climate change is increasingly important when selecting the most suitable genetic resources for forest regeneration. The intention is to increase forest biodiversity and widen the availability of raw wood material by promoting the use of some currently minor tree species. Demand is expected to increase for improved germplasm of such tree species. FGR work in Finland is carried out for all 17 reported species, including those few with current economic importance.

In addition to the economic and environmental benefits of FGR, several country reports highlighted their social and cultural importance, especially for Indigenous Peoples and local communities, many of whom live in forests and base their cultural identity on them. Several studies have found that forests managed by Indigenous Peoples and local communities are often better conserved than other forests, including nearby protected areas (see FAO and FILAC, 2021, and references therein). This is because cultural and traditional management practices foster a sustainable and respectful relationship with the environment, thus promoting natural regeneration and the maintenance of biodiversity. Argentina reported ancestral (and ongoing) seed harvesting customs among Indigenous Peoples that promote natural regeneration by sowing part of the seeds collected for food from species *Araucaria* spp. and certain palms. Argentina also noted that Indigenous Peoples have a deeply rooted cultural appreciation for some tree species, such as araucaria by the Mapuche people and mesquite (*Neltuma* spp., earlier *Prosopis* spp.) by the Chané, Diaguita, Pilagá, Qom and Quechua peoples.

Brazil reported that its forests are home to many Indigenous Peoples and local communities, whose traditional rituals, folklore and culture depend on forests. Various schemes in Brazil are designed to reward the role of these groups in managing forest reserves. The National Fund for Benefit-Sharing, which became operational in 2020, makes it possible for companies that use Brazil's genetic heritage to pay royalties related to the use of the country's flora and fauna. These royalties have generated about USD 1.4 million (Brazilian Development Bank, 2024) for people who preserve and have knowledge of genetic heritage, thus encouraging its sustainable use and conservation. The National Foundation for Indigenous Peoples (Fundação Nacional dos Povos Indígenas) and the Brazilian Agricultural Research Corporation (Empresa Brasileira de Pesquisa Agropecuária) signed a technical cooperation agreement in 2020 to develop value chains and conserve biodiversity on Indigenous lands. This agreement establishes joint activities by the two institutions with Indigenous Peoples in the states of Acre, Alagoas, Bahia, Mato Grosso, Pernambuco, Roraima, Sergipe and Tocantins.

Forests hold significant social and cultural value in Sri Lanka, where more than 80 percent of people still live in rural areas. The country reported that numerous cultural values and functions are ascribed to FGR and that forests play tangible and intangible roles in many aspects of culture, including art, history, language and religion. The national tree of Sri Lanka is Ceylon ironwood (*Mesua ferrea*), and trees play prominent roles in two of the country's widely practised religions, Buddhism and Hinduism (the Bodhi tree, *Ficus religiosa*, and the Banyan tree, *Ficus benghalensis*, respectively).

1.4 Availability of information on forest genetic resources

SoW-FGR1 (FAO, 2014a) showed that the availability of, and access to, information on FGR is poor in many countries. This hampers efforts to improve FGR management and its better integration into forest and cross-sectoral policies. It also hinders global efforts to monitor the status of FGR. Although national forest inventories are in place in many countries, they typically make information available on forest resources in general and do not gather specific data related to the conservation, use and development of FGR (FAO, 2014a). To address this, the Global Plan of Action called for countries to strengthen national FGR monitoring systems and related mechanisms to improve the availability of information on FGR (FAO, 2014b).

Some countries have made progress over the last decade in improving the availability of information on FGR, but the overall situation has not changed significantly. Globally, 49 (64 percent) of the reporting countries have established operational national FGR inventories[2] or similar arrangements, and 12 countries have initiated the establishment of such inventories (Figure 1). In 2012, the year before the adoption of the Global Plan of Action, most (42) reporting countries had already established inventories. Seven countries (China, Ecuador, France, Luxembourg, Malaysia, Mali and Sweden) reported setting up national FGR inventories between 2012 and 2016, but no new inventories have been established since then.

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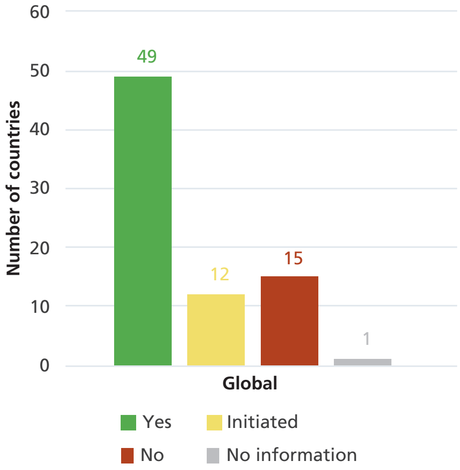
[2] A national (or subnational) FGR inventory is defined as a mechanism that gathers data and information, often from several data providers within a country, on different areas of work on FGR. A national FGR inventory is considered operational when the collection of data and information is repeated frequently and when the data and information are processed, stored and made available to support FGR policymaking, management and research and development.

FIGURE 1

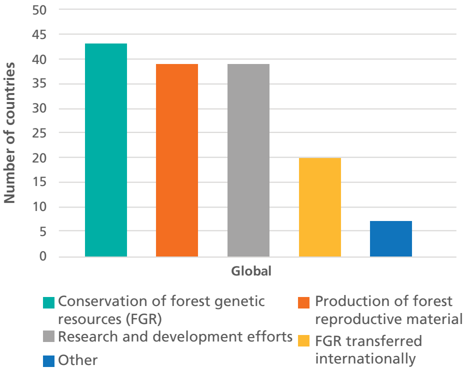
State of operational national forest genetic resource inventories or similar arrangements



Note: Based on country reports.

FIGURE 2

Areas of work documented by national forest genetic resource inventories



Note: Based on country reports.

In several countries, the reported FGR inventories are closely linked to, or are part of, national forest inventories, which have been expanded to gather more data on (for example) species composition and distribution. This is in line with recommendations of SoW-FGR1, which encouraged countries to seek synergies, where possible, with ongoing forest monitoring efforts when improving the documentation of their FGR (FAO, 2014a). The country reports submitted for the present report show that information on FGR is still scattered and that existing FGR inventories often struggle to connect multiple data sources maintained by different stakeholders to gain a comprehensive picture of the status of FGR at the national level.

The challenge of establishing holistic FGR inventories is demonstrated by the different areas of work, as shown in Figure 2. The most common areas of work documented by inventories are FGR conservation (reported by 43 countries), followed by research and development (39 countries) and the production of forest reproductive material (39 countries). An additional 20 countries (mainly in Europe) also reported documenting FGR transferred internationally, and seven countries tracked other related aspects, such as species composition and distribution and species at risk.

SoW-FGR1 also recommended that countries strengthen their FGR information systems to improve access to information for all stakeholders (FAO, 2014a). Countries have made progress in this regard: globally, 42 (55 percent) of the reporting countries now have national FGR information systems[3] or similar arrangements in place, and another 20 countries have initiated the establishment of such systems (Figure 3). In 2012, 35 countries had national FGR information systems; seven more countries (Bulgaria, Burkina Faso, Luxembourg, Mexico, Panama, Sweden and Thailand) had established such systems by 2022.

No country indicated that they have a single database for all aspects of their FGR work, with

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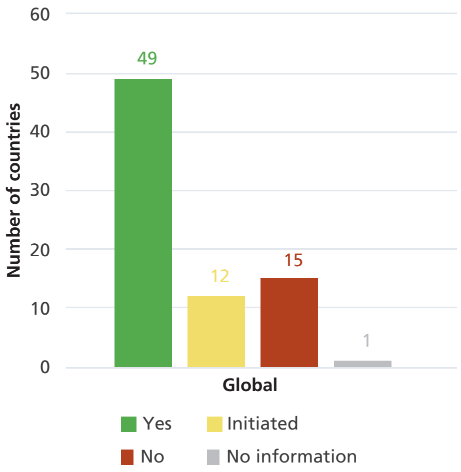
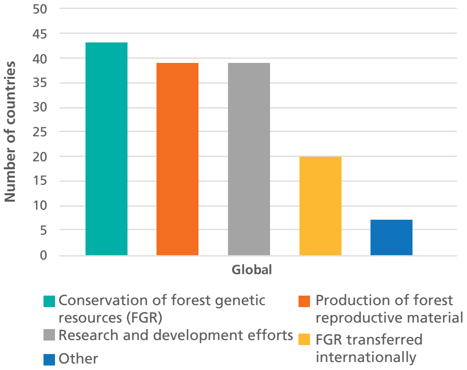
[3] "National (or subnational) FGR information system" refers to a database (or databases) and other electronic documentation systems (offline or online) used by a national FGR inventory to gather, store and/or make available data and information on FGR. A national FGR information system is considered up-to-date when the data and information are updated periodically (e.g. annually) or whenever new data and information become available.

FIGURE 3
State of national forest genetic resource information systems or similar arrangements



Note: Based on country reports.

FIGURE 4
Areas of work recorded by national forest genetic resource information systems



Note: Based on country reports.

countries typically maintaining several databases designed for different purposes. The most common areas of work or activities recorded by information systems are FGR conservation (reported by 35 countries), followed by the production of forest reproductive material (35 countries) and research and development (32 countries) (Figure 4). The information systems of 14 countries record FGR transferred internationally and the systems of five countries record other aspects related to FGR (e.g. taxonomy and threats to species).

In addition to national FGR information systems, regional FGR networks and several international organizations have developed regional or global databases documenting various aspects of FGR. In Asia, a regional project implemented in 2017–2019 under the umbrella of the Asia-Pacific Forest Genetic Resources Programme (APFORGEN) developed range-wide distribution, threat and priority action maps for 63 native Asian tree species. In Europe, the European Forest Genetic Resources Programme (EUFORGEN) maintains the European Information System on Forest Genetic Resources, which, in 2024, contained information on more than 3 400 genetic conservation units for more than 100 tree species in 37 countries. Several botanical and other databases are available at the global level, including Plants of the World Online (POWO) (maintained by the Royal Botanic Gardens, Kew in the United Kingdom of Great Britain and Northern Ireland) and GlobalTreeSearch (developed by Botanic Gardens Conservation International, BGCI). POWO provides information on vascular plants worldwide, and GlobalTreeSearch focuses on the world’s tree species. BCGI launched the Global Tree Portal in 2021 to visualize the data gathered by the Global Tree Assessment initiative. As part of the CGIAR Research Program on Forests, Trees and Agroforestry (2011–2021), World Agroforestry created the Agroforestry Species Switchboard and the Global Tree Knowledge Platform. The Switchboard provides access to more than 50 web-based information sources on trees and other plants covering more than 172 000 plant species and the Platform offers a wide range of tree knowledge products.

Despite the many information systems, it is difficult to draw a complete picture of the state of FGR and the efforts being made at the national, regional and global levels. Country reports indicate that national FGR inventories do not always connect to, or gather data from, all stakeholders involved in FGR work. In addition, some stakeholders may lack access to national FGR information systems. This also applies to the national focal points nominated by countries for coordinating preparation of the country submissions for this report; in many countries, the focal points noted difficulties in accessing and gathering specific information on FGR (e.g. species-specific data on the conservation and use of FGR and tree-breeding efforts).

There are no accessibility issues related to the regional and global information systems because they are all available online, but they only provide information on specific aspects of FGR rather than covering broader topics, such as FGR conservation and the production of forest reproductive material. The regional databases developed by APFORGEN and EUFORGEN are highly appreciated by Asian and European countries, respectively, and the reports of these countries also show that such regional databases have benefited practical FGR conservation at the national level. It seems, however, that many countries worldwide are not fully aware of the global information systems. Thus, the information and knowledge on FGR provided by these systems are not applied at a large scale to advance practical FGR work.

1.5 Contributions of forest genetic resources to sustainable development

The United Nations General Assembly unanimously adopted the 2030 Agenda for Sustainable Development in 2015, with the integrated aims of improving the lives of all people, spurring economic growth, tackling climate change and conserving biodiversity. The 2030 Agenda and its 17 Sustainable Development Goals (SDGs) now constitute the global framework for designing and implementing actions towards sustainable development. Implementation responsibility for reaching the SDGs rests with national governments, supported by international cooperation and partnerships.

Although forests are mentioned explicitly in only SDG 6 (clean water and sanitation) and SDG 15 (life on land), they can contribute to all SDGs (FAO, 2018a). Moreover, efforts to achieve all SDGs by 2030 will affect forests and people dependent on them in many ways (Katila *et al.*, 2019). The impacts can be negative or positive, and achievement of several SDGs will involve trade-offs that have repercussions for people and forests (Katila *et al.*, 2019). It is crucial, therefore, to consider these trade-offs across sectors and to find synergies among the actions taken for achieving the SDGs. For forests and FGR, the linkages between SDGs 2 and 15 require particular attention.

The country reports show that FGR conservation, use and development contribute to sustainable development in many ways. Several countries indicated the most relevant SDGs in their reports, and others stressed the importance of FGR to forest management, biodiversity and climate. SDG 15 is seen as the most relevant goal for FGR, but countries also consider FGR to be important for several other SDGs (Box 1). Nevertheless, the importance of FGR to SDG 2 is often neglected in global policy forums, even though 2.6 billion people rely mostly on woodfuel for household cooking (IEA *et al.*, 2021). Foods provided by woody plant species can also contribute to transforming global food systems (Jansen *et al.*, 2020; Ickowitz *et al.*, 2022). Many tree species contribute to healthy diets and help meet people's micronutrient needs (see the case study in Box 2).

Although all reporting countries indicated that they recognized the importance of FGR for sustainable development, FGR are not mentioned in any SDG targets and indicators. In contrast, PGRFA and animal genetic resources for food and agriculture (AnGRFA) are included in SDG 2 targets and indicators and are monitored using country data gathered by FAO for this purpose and for Commission assessments (FAO, 2019a). FGR were not reflected in the Aichi Biodiversity Targets adopted by the Convention on Biological

BOX 1.

The most relevant Sustainable Development Goals for forest genetic resources, based on country reports

1 NO POVERTY	**Goal 1**	End poverty in all its forms everywhere.
2 ZERO HUNGER	**Goal 2**	End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
6 CLEAN WATER AND SANITATION	**Goal 6**	Ensure availability and sustainable management of water and sanitation for all.
7 AFFORDABLE AND CLEAN ENERGY	**Goal 7**	Ensure access to affordable, reliable, sustainable and modern energy for all.
13 CLIMATE ACTION	**Goal 13**	Take urgent action to combat climate change and its impacts.
15 LIFE ON LAND	**Goal 15**	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

Diversity (CBD) for the period 2011–2020 (CBD, 2010), which might explain why FGR were omitted from the SDG targets and indicators.

Two years after it adopted the 2030 Agenda, the UN General Assembly also adopted the UN Strategic Plan for Forests for the period 2017–2030 (UN, 2017). This plan provides a global framework for actions at all levels to sustainably manage all types of forests and trees outside forests and to halt deforestation and forest degradation. It includes six Global Forest Goals (GFGs) (Box 3) and 26 associated targets to be achieved by 2030. These voluntary goals and targets contribute to the implementation of the 2030 Agenda, the Paris Agreement, the CBD and the UN Convention to Combat Desertification. None of the GFG targets refer to FGR, but "conservation and sustainable use of genetic diversity of forests and trees outside forests" is listed as one of the indicative thematic areas for action under GFG 2.

Progress towards the GFGs is assessed based on voluntary national reports and a global core set of forest-related indicators. Most of the core indicators are established but some need further conceptual and methodological work and are not yet operational (UNFF, 2021). The existing core indicators do not include a specific indicator on FGR, but some countries have reported their actions on FGR under GFGs 1 and 4 (UNFF, 2021).

BOX 2

Supporting healthy diets with food trees

Micronutrient deficiencies affect more than 2 billion people globally, and more than one-third of adults are considered overweight or obese. In many parts of the world, this is due partly to excessive reliance on a small number of calorie-rich but otherwise nutrient-poor staple crops. Nutrient-rich tree foods are important diversifiers of food systems and, with the right interventions, can play a greater role in supporting healthier human diets (Ickowitz *et al*., 2022). This will require the promotion of a broader range of tree foods in food systems in context-specific ways that address the particular needs and preferences of communities and consider the prevailing farming environment.

To facilitate the consumption of foods sourced especially from native trees, the Center for International Forestry Research and World Agroforestry (CIFOR–ICRAF) and its partners have worked with rural communities in East Africa to test "food tree portfolios" (McMullin *et al.,* 2019). These portfolios, when combined with other crops, can supply micronutrient needs over an entire year and fill gaps in food production calendars. The promotion of food trees not only supports food system diversification and human diets, it also results in the retention of more biodiversity in landscapes and the provision of other ecosystem services.

Portfolio design is a multi-step process. The first step is to determine, through farmer-household interviews, the crops already grown by farmers and the foods that household members consume. These data are used to determine, at a "resolution" of months, periods in which households experience food insecurity and the key micronutrient gaps. Recommendations for nutrient-rich food trees have focused on the provision of vitamins A and C, iron and folate because these micronutrients are priorities for public health and can be found in high quantities in many tree foods. Portfolios are also based on inventories of the tree foods found around farms, the fruit production phenology of species, and the cultural preferences of local people. In this way, meaningful matches are made between production and dietary gaps. Once the portfolios are designed, seedlings of specific species produced in tree nurseries developed by farmer groups, nursery businesses and schools can be supplied to communities. The portfolio approach emphasizes the cultivation of underused native tree species that have received little attention in the past because these have latent potential for significant dietary impact. In Kenya, for example, the portfolios have been designed to include native trees such as baobab (*Adansonia digitata*), desert date (*Balanites aegyptiaca*), mbola plum (*Parinari curatellifolia*) and tamarind (*Tamarindus indica*).

To date, 15 portfolios of tree species – along with complementary vegetables, pulses and staple crops – have been developed for sites in East Africa, and the approach is now being deployed in new areas. Pilot upscaling projects of the approach in Ethiopia, Kenya and Uganda have reached 1 800 smallholder households. In addition, 6 000 farmers, half of whom are women, have been trained in food-tree cultivation and use, and a further 11 000 farmers have been reached through outreach events. Kenya has initiated further work to test, propagate and distribute 15 priority food-tree species.

CIFOR–ICRAF is exploring the combination of interventions needed to maximize the adoption of the portfolio approach (McMullin, *et al.,* 2021). There is a need to characterize the nutrient compositions of more native tree species because, in many cases, this information is absent or incomplete, which means there is a risk of overlooking them in programmes and policies.

Sources: **Ickowitz, A., McMullin, S., Rosenstock, T., Dawson, I., Rowland, D., Powell, B., *et al.*** 2022. Transforming food systems with trees and forests. *Lancet Planetary Health,* 6: e632-e639. https://doi.org/10.1016/S2542-5196(22)00091-2; **McMullin, S., Njogu, K., Wekesa, B., Gachuiri, A., Ngethe, E., Stadlmayr, B., *et at.*** 2019. Developing fruit tree portfolios that link agriculture more effectively with nutrition and health: A new approach for providing year-round micronutrients to smallholder farmers. *Food Security,* 11: 1355–1372; **McMullin, S., Stadlmayr, B., Mausch, K., Revoredo-Giha, C., Burnett, F., Guarino, L. *et al.*** 2021. Determining appropriate interventions to mainstream nutritious orphan crops into African food systems. *Global Food Security,* 28: article 100465. https://doi.org/10.1016/j.gfs.2020.100465

The lack of specific FGR targets and indicators in the SDGs, Aichi Biodiversity Targets and GFGs is surprising, given that FGR have long been elements of sustainable forest management (e.g. Wilkie, Holmgren and Castañeda, 2003) and that the importance of forest genetic diversity is recognized in many decisions of the Conference of the Parties to the CBD. Most regional and ecoregional processes that helped translate the concept of sustainable forest management into practice by developing criteria and indicators for it also developed specific targets and indicators for FGR (McKinnell, 2002), which have since been used for monitoring implementation of sustainable forest management in (for example) Europe (FOREST EUROPE, 2020) and Montréal Process countries (Montréal Process, 2015).

Given the neglect of genetic diversity in previous CBD monitoring and reporting (Laikre, 2010; Laikre, *et al.*, 2010), it is encouraging that the Kunming–Montreal Global Biodiversity Framework, which was adopted at 15th Conference of the Parties to the CBD in December 2022, includes – in Goal A for 2050 and Target 4 for 2030 – the conservation of genetic diversity of all species. Progress towards Goal A and Target 4 will be monitored by means of one headline indicator (A.4: "The proportion of populations within species with an effective population size > 500"), complemented by several optional component and complementary indicators. Work is underway to operationalize the monitoring system of the Kunming–Montreal Global Biodiversity Framework.

By confirming the importance of the genetic diversity of domesticated and wild species, the Kunming–Montreal Global Biodiversity Framework is expected to increase awareness of the importance of FGR, the lack of which was noted as a problem in many country submissions for the present report. Sweden, for example, commented that FGR was seldom discussed by policymakers, managers and scientists in relation to relevant SDGs and that, in the case of biodiversity, the attention was often limited to the ecosystem and species levels. Sweden also noted a need to increase awareness of the importance of FGR in Swedish forests and forestry and that FGR must be addressed more systematically and be better integrated into strategies for biodiversity conservation and sustainable forest management.

In its report, Argentina emphasized the need to raise awareness among policymakers and the public of the importance of conserving FGR under climate change, as well as the crucial role of Indigenous Peoples and local communities in managing forests.

China reported that, although FGR has made great contributions to sustainable development, the public was still unaware of the importance of FGR compared with that of AnGRFA and PGRFA. China also noted that the lack of publicity given by relevant organizations to the value and importance of FGR contributed to the lack of public awareness. To address this, China's national action plan for the conservation and sustainable use of FGR (2015–2025), developed by the National Forestry and Grassland Administration, includes a specific action to "establish a publicity mechanism to raise public awareness of the importance of FGR". Under this action, efforts are underway to make full use of various media channels to increase public awareness of FGR, disseminate knowledge on FGR, and popularize science on FGR in protected areas, forest parks, botanic gardens and other places.

Sri Lanka pointed out that the obstacles to increased awareness are varied and complex, including a lack of adequate funding for FGR work and limited institutional support and coordination among agencies and stakeholders. To address these obstacles, Sri Lanka noted that a multistakeholder approach involving effective institutional coordination, increased funding and awareness-raising efforts is essential.

In some countries, awareness of the importance of FGR among policymakers, other stakeholders and the public is reportedly relatively high, although this does not mean it is easy to maintain or increase investments in FGR work, including research and capacity development. Canada, for example, reported that awareness of FGR was relatively high, with provincial and federal government departments broadly recognizing the value of genetic diversity as a source of sustainable economic growth through tree improvement and a resource for forest conservation. The country's forest industry is also keen to ensure adequate supplies of high-quality seeds and improved germplasm for reforestation. Moreover, numerous Canadian universities conduct research and training on FGR in collaboration with provincial programmes, advancing basic research that will benefit FGR management and breeding programmes. Canada noted that FGR are valued to varying degrees by non-governmental organizations. Some, such as the Whitebark Pine Ecosystem Foundation of Canada and Ontario's Forest Gene Conservation Association, are fully aware of the value of FGR, but others with broader mandates do not explicitly recognize genetic values. Canada reported that the biggest constraint on maintaining awareness of the value and importance of FGR is a lack of financial resources. Although some provinces have a history of strong support for FGR (e.g. British Columbia, where industry and government have supported a forest genetics programme for about 60 years), many jurisdictions have struggled to maintain FGR programmes and train professionals in FGR because of diminishing funds.

1.6 Conclusions

Forests and trees are crucial for people, biodiversity and the climate, and they also make important contributions to other aspects of sustainable development. The many benefits offered by forests and trees, underpinned by FGR, are not limited to the forest sector and extend into agriculture and even fisheries. Nevertheless, policymakers and the public often overlook the value and importance of FGR for sustainable development, biodiversity and climate change.

The country reports show many examples of how the conservation, use and development of FGR have contributed to the efforts of countries towards sustainable development. Several also noted that

BOX 3.

Global Forest Goals

Goal 1	Reverse the loss of forest cover worldwide through sustainable forest management, including protection, restoration, afforestation and reforestation, and increase efforts to prevent forest degradation and contribute to the global effort of addressing climate change.
Goal 2	Enhance forest-based economic, social and environmental benefits, including by improving the livelihoods of forest-dependent people.
Goal 3	Increase significantly the area of protected forests worldwide and other areas of sustainably managed forests, as well as the proportion of forest products from sustainably managed forests.
Goal 4	Mobilize significantly increased, new and additional financial resources from all sources for the implementation of sustainable forest management and strengthen scientific and technical cooperation and partnerships.
Goal 5	Promote governance frameworks to implement sustainable forest management, including through the United Nations Forest Instrument, and enhance the contribution of forests to the 2030 Agenda for Sustainable Development.
Goal 6	Enhance cooperation, coordination, coherence and synergies on forest-related issues at all levels, including within the United Nations system and across member organizations of the Collaborative Partnership on Forests, as well as across sectors and relevant stakeholders.

FGR offer opportunities for adapting to climate change, improving productivity and developing new products that would merit further research, should more human and financial resources be available. Practical work on FGR is hampered in many countries by a lack of adequate funding and institutional and technical capacity.

The Global Plan of Action identified strategic priorities to increase awareness of the value of FGR, strengthen national capacities for FGR work, and mobilize resources for this (FAO, 2014b). The present report suggests that progress on these priorities has been varied to date among reporting countries. Many highlighted the continued need to increase awareness among policymakers and the public of the value and importance of FGR. Insufficient awareness is a likely reason for the lack (or low level) of resources made available for FGR work. Therefore, these strategic priorities remain highly relevant to future efforts.

It is likely that the limited awareness of the importance of FGR is linked to challenges in gathering information on these resources and making it accessible to all stakeholders. The Global Plan of Action identified FGR information as one of its priority areas, but progress in this area has been minimal, with only seven additional countries establishing national FGR inventories or information systems in the last decade. FGR inventories and information systems are in place in 64 and 55 percent of reporting countries, respectively, but this does not mean that information on FGR is being gathered and analysed systematically to connect different areas of FGR work. Given that 57 percent of the Commission's members failed to submit country reports for the present report, it seems that most countries do not collect even basic information on FGR that would guide policymakers and practitioners in their decisions and actions.

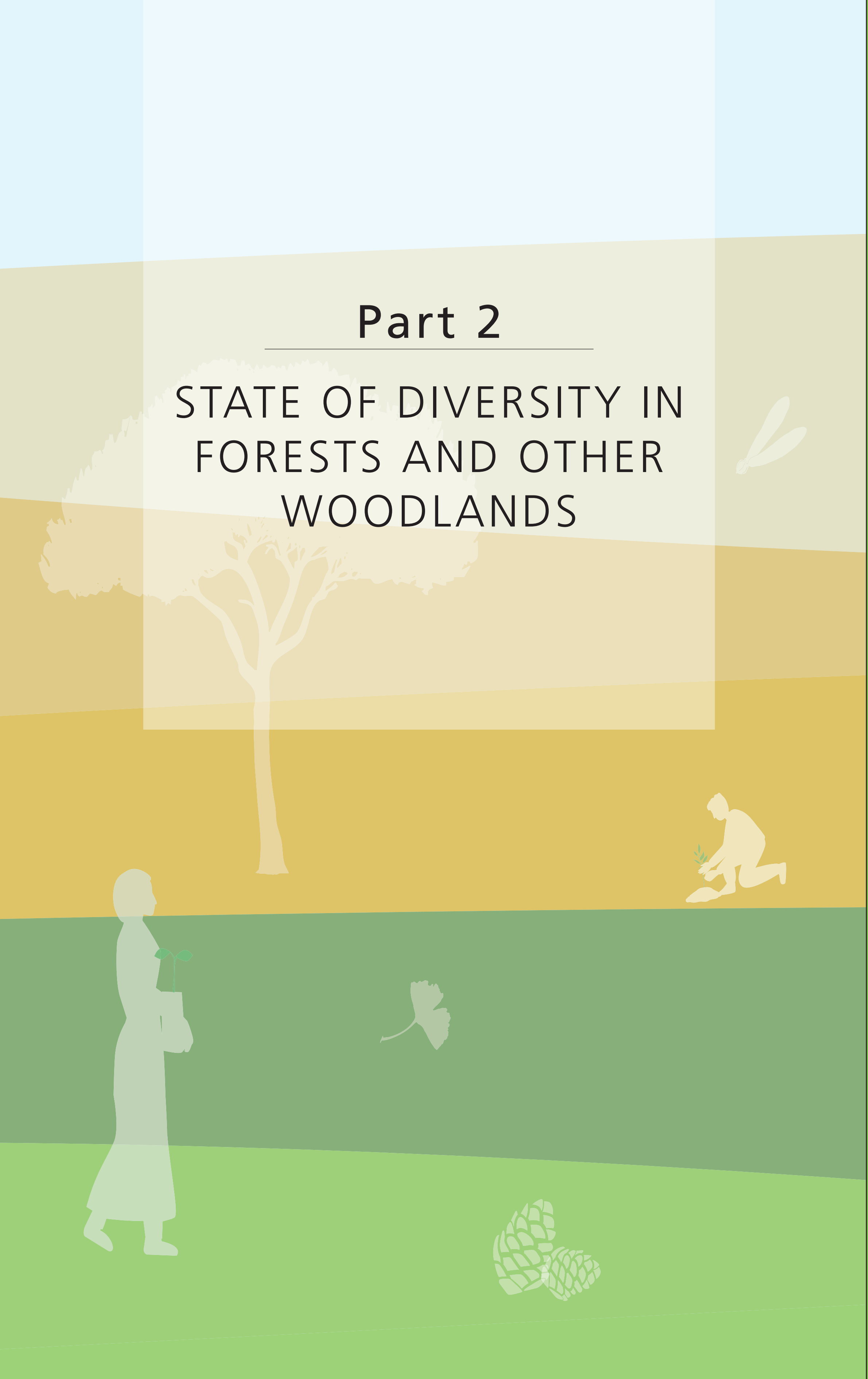
At the international level, the value and importance of FGR is neglected in relation to sustainable development, biodiversity conservation and climate action, as well as in efforts to promote the implementation of sustainable forest management. The Kunming–Montreal Global Biodiversity Framework offers an opportunity to raise global awareness of the importance of genetic diversity of all species, including forest trees and other woody plant species.

The halfway point in efforts to achieve the SDGs (and several other international forest-related goals) by 2030 was passed in 2023. Progress towards the SDGs has been fragile and slow, and the world seems to be falling far short of achieving them all (UN, 2023). It is also questionable whether all the GFGs will be achieved by 2030 (UNFF, 2021). The slow progress has led to calls to intensify efforts with new investments in the remaining years, offering opportunities to strengthen implementation of the Global Plan of Action and demonstrate the value and importance of FGR to policymakers and the public.

SoW-FGR1 suggested in 2014 that, "the future value of FGR will be determined by the way humans manage these resources and act in their role as the primary agents of environmental change in today's world" (FAO, 2014a). New information on forests, trees and FGR has been acquired across the world since then. Following chapters present this and other new information and analyse the progress made in managing FGR and enhancing capacities and polices.

Part 2

STATE OF DIVERSITY IN FORESTS AND OTHER WOODLANDS



Chapter 2

State of the forests

2.1 Introduction

At the request of its Members, FAO collects, analyses and disseminates information on the status of, and trends in, the world's forest[4] resources through its Global Forest Resources Assessments (FRAs). The first FRA were published in 1948; since then, FAO has reported on the world's forests at intervals of 5–10 years to provide a consistent approach to describing the world's forests and how they are changing. The most recent FRA (FAO, 2020; hereafter "FRA 2020") was published in 2020 (the next edition will be published in 2025).

Early FRAs focused on timber availability but recent assessments have taken a more holistic perspective (FAO, 2018b). The means of assessment have also changed, from expert-driven exercises to a process that relies on country data provided by a well-established worldwide network of government-nominated national correspondents and their collaborators.

Starting with FRA 2005 (FAO, 2006), FAO collaborates with other international reporting processes and organizations involved in the collection of forest-related data. It also works with other members of the Collaborative Partnership on Forests[5] to improve definitions and streamline reporting. This approach led to the establishment of the Collaborative Forest Resources Questionnaire,[6] which was first used in the preparation of FRA 2015 (FAO, 2015). In consultation with countries and international experts, FAO reviews the scope of forthcoming FRAs to avoid overlaps with other data-collection processes, reduce the reporting burden and ensure the relevance of the report's content.

FRA 2020 examined status and trends for about 60 categories of variable (under seven main topics) for the period 1990–2020. The backbone of the assessment were data reported in standardized country reports compiled by national correspondents via an online platform. More than 700 experts from 187 countries and territories were directly involved in the process. For the first time, all the data and metadata reported were made available to users through an online platform in an easy-to-use digital format (FAO, 2020).

In the context of the FRA 2020 process, FAO conducted a global remote-sensing survey (the FRA Remote Sensing Survey – RSS) with the aim of generating independent, robust and consistent estimates of forest area and their changes over time at the global, regional and

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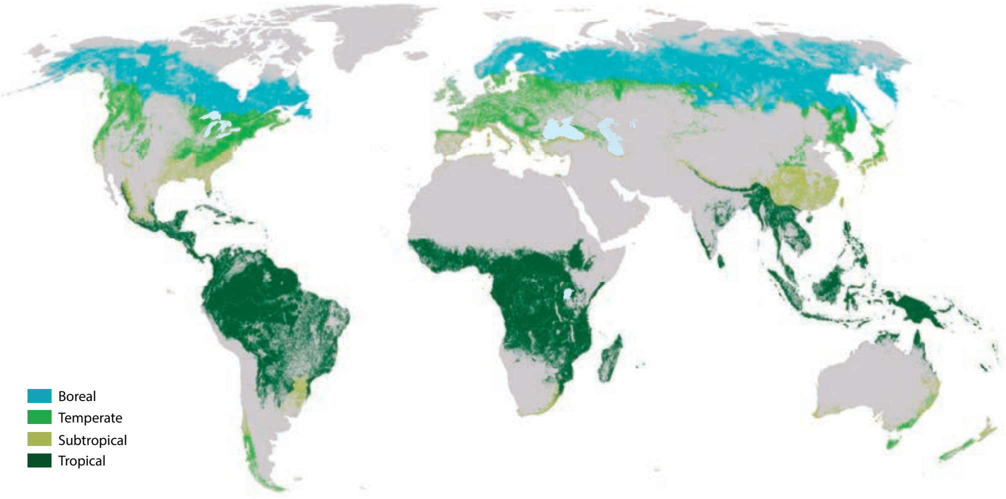
[4] FAO defines "forest" as land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10 percent, or trees able to reach these thresholds *in situ*. It does not include land that is predominantly under agricultural or urban land use. See FAO (2018) for more through documentation of the terms and definitions used in this chapter.

[5] Further information at https://www.fao.org/collaborative-partnership-on-forests/en

[6] The Collaborative Forest Resources Questionnaire partners are FAO, FOREST EUROPE, the International Tropical Timber Organization, the United Nations Economic Commission for Europe, the Observatory of Central African Forests and the Montréal Process.

FIGURE 5

The global distribution of forests, by climatic domain



Note: The boundaries shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.
Source: FAO. 2020. *Global Forest Resources Assessment 2020: Main report*. Rome. https://doi.org/10.4060/ca9825en

biome levels. The survey was also designed to help strengthen the capacity of countries to use remote sensing for forest monitoring. The RSS was a separate effort from the country reporting process based on the visual interpretation of more than 400 000 samples globally by a network of more than 800 national experts in 126 countries. In addition to confirming many of the results of the FRA country reporting process, the RSS produced novel information on drivers of deforestation and several other aspects of forest resources not comprehensively covered by the country reporting process (FAO, 2022c).

The results presented in this chapter are based on these two global assessments.

2.2 The extent of forests

The global forest area is estimated at 4.06 billion ha, which is 31 percent of the total land area (FAO, 2020). Most of the world's forests are found in the tropical biome, which accounts for 45 percent of the global forest area, followed by the boreal (27 percent), temperate (16 percent) and subtropical (11 percent) domains (FAO, 2020; see also Figure 5). Table 1 shows the distribution of forests by region – Europe, including the Russian Federation, (26 percent) and Latin America and the Caribbean (23 percent) account for nearly half the global forest area.

The total forest area decreased by 178 million ha between 1990 and 2020 (FAO, 2020). The annual rate of net forest loss decreased from 7.84 million ha in 1990–2000, to 5.17 million ha in 2000–2010, to 4.17 million ha in 2010–2020. African countries collectively reported the highest net loss of forest area (3.67 million ha per year) in the decade to 2020, followed by Latin America and the Caribbean (2.81 million ha per year). Asia had the highest annual net gain in forest area in 2010–2020, at 1.03 million ha, followed by Europe, at 470 000 ha.

FRA 2020 also collected data on the components of forest-cover change – forest expansion (afforestation and natural expansion) and deforestation (conversion of forest to other land uses).

TABLE 1
Forest area by region, 2020

Region	Total forest area (1 000 ha)	% of world forest area	Primary forest area (1 000 ha)
Africa	612 032	15	148 000
Asia	574 594	14	84 400
Europe	1 044 277	26	260 000
Latin America and the Caribbean	940 171	23	332 000
Near East	45 885	1	2 730
North America	656 724	16	280 000
Southwest Pacific	185 248	5	2 620
World	**4 058 931**	**100**	**1 110 000**

Source: FAO. 2020. *Global Forest Resources Assessment 2020: Main report*. Rome. https://doi.org/10.4060/ca9825en

An estimated 420 million ha of forest was lost globally through deforestation between 1990 and 2020, although the rate slowed over the period. The global annual rate of deforestation declined from 15.8 million ha in 1990–2000 to 15.1 million ha in 2000–2010, 11.8 million ha in 2010–2015 and 10.2 million ha in 2015–2020 (FAO, 2020) (Table 2).

More than 90 percent of deforestation between 1990 and 2020 was recorded in the tropical domain; the annual rate there declined from 13.8 million ha in 1990–2000 to 9.28 million ha in 2015–2020. A significant decrease in annual deforestation was also observed in the subtropical domain, where it dropped from 1.4 million ha in 1990–2000 to 0.5 million ha in 2015–2020.

Of the regions, the highest annual deforestation rate in 2015–2020 was in Africa (4.07 million ha), followed by Latin America and the Caribbean (3.30 million ha) and Asia (2.14 million ha). The deforestation rate has increased in Africa since 1990, but it almost halved between 1990 and 2020 in Asia and Latin America and the Caribbean. The RSS produced information on deforestation by global ecological zones, which constitute a subdivision of global climatic domains (FAO, 2010a). According to the RSS, tropical forests accounted for more than 90 percent of global deforestation in 2000–2018, with tropical rainforests comprising 40 percent of total forest losses. The global ecological zones with the second- and third-highest deforestation rates were tropical moist forest and tropical dry forest, at 27 and 19 percent, respectively, of global deforestation between 2000 and 2018 (FAO, 2022c).

The RSS estimated the proportion of forest area deforested since 2000 by ecoregion (ecoregions are a combination of FRA's geographical subregions and global ecological zones; FAO, 2022c). The tropical ecoregion of Central America had the highest proportion of deforestation between 2000 and 2018: an estimated 30 percent of forest in the tropical moist ecoregion and 25 percent of tropical dry forest, rainforest and shrubland ecoregions were lost in Central America in 2000–2018. These estimates should be interpreted with care, given the low number of samples in this ecoregion and the resultant high sampling errors of the estimates (FAO, 2022c).

2.3 Forest characteristics

The FRA identifies two broad categories of forest: naturally regenerating forest, and planted forest (FAO, 2018b). FRA 2020 collected information on both categories, as well as on certain subcategories of planted forest. Naturally regenerating forests accounted for 93 percent (3.75 billion ha) of the total forest area in 2020. Europe had the largest area in this forest category, followed by Latin America and the Caribbean, North America, Africa, Asia, the Southwest Pacific and the Near East.

The area of naturally regenerating forests decreased by 301 million ha between 1990 and 2020 (FAO, 2020). The overall rate of loss slowed in each ten-year period, from an average of 11.9 million ha per year in 1990–2000 to 7.84 million ha per year in the most recent decade (Table 3).

The area of naturally regenerating forest decreased between 2010 and 2020 in all areas except Europe and the Southwest Pacific. The

TABLE 2

Global forest expansion and deforestation, 1990–2020, by region

Region	Forest expansion (1 000 ha/year)					Deforestation (1 000 ha/year)				
	1990–2000	2000–2010	2010–2015	2015–2020	2010–2020	1990–2000	2000–2010	2010–2015	2015–2020	2010–2020
Africa	510.6	623.3	360.5	351.2	355.9	3 615.8	3 855.1	4 091.7	4 072.5	4 082.1
Asia	4 203.0	4 699.4	3 725.8	3 309.1	3 517.4	4 089.2	2 597.7	2 830.4	2 142.2	2 486.3
Europe	930.7	1 397.8	780.5	628.1	704.3	91.3	131.8	284.0	162.2	223.1
Latin America and the Caribbean	1 301.1	1 794.9	846.8	569.8	708.3	6 757.8	7 330.2	3 741.9	3 300.6	3 521.2
Near East	349.4	404.5	121.2	119.9	120.6	557.9	504.7	364.7	341.8	353.2
North America	115.9	520.9	275.0	0.0	137.5	54.4	50.5	41.3	97.5	69.4
Southwest Pacific	490.7	430.3	1 141.8	205.3	673.6	655.3	661.7	457.9	42.5	250.2
WORLD	7 901.5	9 871.1	7 251.7	5 183.4	6 217.5	15 821.8	15 131.7	11 811.8	10 159.3	10 985.5

Source: FAO. 2020. *Global Forest Resources Assessment 2020: Main report*. Rome. https://doi.org/10.4060/ca9825en

TABLE 3

Annual change in the area of naturally regenerating forest, by region, 1990–2020

Region	Naturally regenerating forest					
	1990–2000		2000–2010		2010–2020	
	Area	Rate	Area	Rate	Area	Rate
	(1 000 ha/year)	(%)	(1 000 ha/year)	(%)	(1 000 ha/year)	(%)
Africa	–3 065.6	–0.45	–3 322.3	–0.51	–3 765.1	–0.61
Asia	–1 859.5	–0.40	–407.0	–0.09	–502.2	–0.11
Europe	57.2	0.01	251.5	0.03	198.5	0.02
Latin America and the Caribbean	–5 700.8	–0.55	–6 120.5	–0.62	–3 378.3	–0.36
Near East	–218.1	–0.45	–150.5	–0.32	–244.3	–0.55
North America	–877.5	–0.14	–293.0	–0.05	–542.4	–0.09
Southwest Pacific	–263.8	–0.15	–303.0	–0.17	–391.2	–0.22
WORLD	–11 928.1	–0.30	–10 344.8	–0.27	–7 842.7	–0.21

Note: The rate of change (%) is calculated as the compound annual change rate.

Source: FAO. 2020. *Global Forest Resources Assessment 2020: Main report*. Rome. https://doi.org/10.4060/ca9825en biggest losses were in Africa, where Angola alone reported an average annual loss of 548 000 ha in 2010–2020.

The rate of loss of naturally regenerating forests declined by almost half (41 percent) in Latin America and the Caribbean between 2000–2010 and 2010–2020, from 5.70 million ha to 3.38 million ha. This was due mainly to Brazil, where the average annual loss declined from 4.32 million ha in 2000–2010 to 1.89 million ha in 2010–2020. Although the area of naturally regenerating forest also declined in Asia, the average annual losses in 2010–2020 were significantly lower than in Latin America and the Caribbean, at 502 000 ha. The area of naturally regenerating forest increased in Europe and the Southwest Pacific in 2010–2020.

Primary forests are naturally regenerating forests composed of native tree species where there are no clearly visible indications of human activities (FAO, 2018b), and ecological processes in these forests are not significantly disturbed. Primary forests – especially primary tropical moist forests – are highly species-rich and diverse, and their extent is an important environmental indicator of the status of biodiversity conservation. Table 3 shows that Latin America and the Caribbean had the largest area of primary forests in 2020, at 332 million ha, followed by North America and Europe (including the Russian Federation).

Note that many countries and territories based their estimates of primary forest status and trends on proxies, which reduces the reliability of the findings presented here. Therefore, the results should be treated with caution.

FRA 2020 estimated the total area of planted forests in 2020 at 294 million ha, which was 7 percent of the global forest area. Asia had the largest area, at 132 million ha, as well as the highest percentage of planted forest (24 percent) as a proportion of total forest area. Eight percent of planted forests was in Europe and 2 percent was in Africa.

Globally, the area of planted forests increased by 123 million ha between 1990 and 2020, with increases in all regions. The average annual rate of global increase peaked in 2000–2010, at 5.13 million ha, compared with 4.06 million ha in 1990–2000 and 3.06 million ha in 2010–2020 (Table 4).

Although most of the increase in planted forest in 2010–2020 was in Asia, the average annual rate of gain was substantially less in that region than in the previous decade. This mainly reflected a decrease in the rate of gain in China, which reported annual increases in planted forest area of 1.85 million ha in 2000–2010 and 1.14 million ha in 2010–2020.

The planted-forest category can be further divided into plantation forest and other planted forest (Figure 6). Globally, there were 131 million ha of plantation forests in 2020, which was 45 percent of the total planted-forest area. The remainder (55 percent), categorized as other planted forest, covered 163 million ha.

The highest share of plantation forests in 2020 was in Latin America and the Caribbean, where this subcategory constituted about 98 percent of the total area of planted forests. Plantation forests also accounted for most (91 percent) of the total planted-forest area in the Southwest Pacific, about two-thirds (67 percent) in Africa, and more than half (58 percent) in Asia. Other planted forests predominated in Europe, at 93 percent of the total planted-forest area, and in North America, at 69 percent.

The area of plantation forests worldwide increased by 55.8 million ha between 1990 and 2020, with the biggest jump (21.2 million ha) occurring in 2000–2010. The average annual rate of gain increased from 1.98 million ha in 1990–2000 to 2.12 million ha in 2000–2010, before falling to 1.48 million ha per year in 2010–2020.

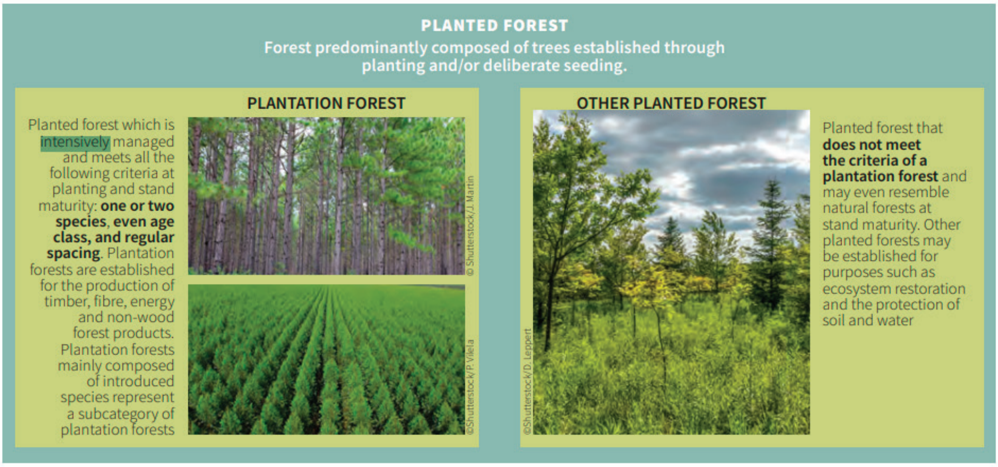
Globally, the area of plantation forest composed of introduced species was estimated at 49.7 million ha in 2020, which was 1.4 percent of the total forest area of reporting countries and 44 percent of the total plantation-forest area in the reporting countries. The largest area of plantation forest composed of introduced species was in Asia, at 20.8 million ha (32 percent of the total area of plantation forest in that region), followed by Latin America and the Caribbean, at 18.0 million ha.

TABLE 4
Annual change in the area of planted forest, by region, 1990–2020

Region	Planted forest					
	1990–2000		2000–2010		2010–2020	
	1 000 ha/year	Rate (%)	1 000 ha/year	Rate (%)	1 000 ha/year	Rate (%)
Africa	40.0	0.48	169.5	1.83	78.3	0.74
Asia	1 973.3	2.45	2 508.6	2.44	1 533.5	1.24
Europe	758.9	1.29	983.5	1.46	230.0	0.31
Latin America and the Caribbean	244.2	2.81	585.0	4.68	565.6	3.09
Near East	5.5	0.38	48.1	2.84	12.8	0.63
North America	939.0	3.54	763.4	2.17	610.5	1.44
Southwest Pacific	99.1	3.09	71.6	1.75	32.1	0.69
WORLD	4 060.1	2.16	5 129.6	2.20	3 062.9	1.11

Source: FAO. 2020. *Global Forest Resources Assessment 2020: Main report*. Rome. https://doi.org/10.4060/ca9825en

FIGURE 6.
Components of planted forests



PLANTED FOREST
Forest predominantly composed of trees established through planting and/or deliberate seeding.

PLANTATION FOREST

Planted forest which is intensively managed and meets all the following criteria at planting and stand maturity: **one or two species**, **even age class, and regular spacing**. Plantation forests are established for the production of timber, fibre, energy and non-wood forest products. Plantation forests mainly composed of introduced species represent a subcategory of plantation forests

OTHER PLANTED FOREST

Planted forest that **does not meet the criteria of a plantation forest** and may even resemble natural forests at stand maturity. Other planted forests may be established for purposes such as ecosystem restoration and the protection of soil and water

Source: **FAO**. 2020. *Global Forest Resources Assessment 2020: Main report.* Rome. https://doi.org/10.4060/ca9825en

The area of other planted forest increased by 66.8 million ha between 1990 and 2020, with the average annual rate of gain increasing from 2.08 million ha in 1990–2000 to 3.01 million ha in 2000–2010 before dropping to 1.59 million ha in 2010–2020.

2.4 The management and ownership of forests

FRA 2020 collected data on the status of, and trends in, the primary designated management objective – that is, the main intended purpose for which a forest is managed and used (Table 5).

TABLE 5
Six broad management objective categories explained

Forest category	Management objective
1. Production	The production of timber, fibre, bioenergy and/or non-wood forest products
2. Protection of soil and water	The protection of soil and water
3. Conservation of biodiversity	Biodiversity conservation. This category includes but is not limited to areas designated for biodiversity conservation in protected areas
4. Social services	The provision of social services such as recreation, tourism, education, research and the conservation of cultural or spiritual sites
5. Multiple use	A combination of several purposes, none of which is significantly more important than another. Thus, a designation of multiple use indicates that the forest is managed for any combination of production, soil and water protection, biodiversity conservation and the provision of social services
6. Other	Other than production, the protection of soil and water, biodiversity conservation, social services or multiple use

Source: FAO. 2020. *Global Forest Resources Assessment 2020: Main report*. Rome. https://doi.org/10.4060/ca9825en

To be considered "primary", the management objective must be significantly more important than other management objectives, and the forest area reported under a given primary management objective may not be reported under any other primary management objective. It should be kept in mind, however, that many forests are managed for multiple purposes and that the primary management objective does not exclude the provision of other benefits or values. For example, sustainably managed naturally regenerating production forests – for which the primary objective might be wood production – typically also contribute to the protection of soil and water, biodiversity conservation and the provision of social services.

Globally, the production of wood and non-wood products was the main designated objective for forest management in 2020, accounting for 31 percent of the total forest area, followed by multiple use, at 22 percent. Twelve percent of the total forest area was designated primarily for the protection of soil and water and 11 percent was designated primarily for biodiversity conservation. The provision of social services was the primary management objective for 6 percent of the world's forests, and "other purposes", which includes areas of forest managed primarily for scientific research or military and defensive purposes, accounted for 7 percent. The remaining part of the world's forests had no designation, or the designation was unknown.

Of the regions, the largest share of forest area designated for production was in Europe, with more than half the forest area assigned to this purpose. If the Russian Federation is excluded, however, the proportion was about 30 percent of the forest area, which is similar to the proportion in Asia.

Regions with the largest shares of forest area designated for multiple use were North America, the Near East and Latin America and the Caribbean. Asia had the largest share of forest area designated primarily for the protection of soil and water.

The forest area designated primarily for biodiversity conservation in 2020 was estimated at 424 million ha, which was 11 percent of the total forest area of the reporting countries. The largest area of forest designated for biodiversity conservation was in Africa (99.6 million ha); this was 24 percent of the forest area in that region, which was the highest proportion among the regions. The lowest proportion was in Europe (including the Russian Federation), at 4 percent.

The area of forest designated primarily for biodiversity conservation increased by 111 million ha between 1990 and 2020, with the largest increase occurring between 2000 and 2010. The average annual increase grew from 3.60 million ha in 1990–2000 to 5.13 million ha in 2000–2010 but dropped by more than half in 2010–2020, to

2.34 million ha. This global trend was evident in all regions except Europe and Latin America and the Caribbean, where the rate of increase decreased in each successive decade between 1990 and 2020. The biggest increase in the area of forest designated primarily for biodiversity conservation between 1990 and 2020 was in Asia, at 25.2 million ha, followed by North America (23.1 million ha) and Europe (21.0 million ha). The biggest increases between 1990 and 2020 in the proportion of total forest area designated primarily for biodiversity conservation were in Africa (from 18 percent in 1990 to 24 percent in 2020) and the Southwest Pacific (from 11 percent to 17 percent).

The area of forest designated for biodiversity conservation is linked to the establishment of protected areas, which are areas identified as important for the long-term conservation of nature and managed for that purpose (Dudley, 2008). In FRA 2020, countries were requested to provide information on the area of forest in formally established protected areas that corresponded to International Union for Conservation of Nature (IUCN) protected-area categories I–IV (Dudley and Phillips, 2006). Information was also collected on the area and proportion of forests with long-term management plans that are documented and periodically revised. These two attributes are components of Sustainable Development Goal indicator 15.2.1 ("progress towards sustainable forest management"), which is reported annually by FAO to the United Nations Statistics Division.

The total area of forest in legally protected areas in 2020 was estimated at 726 million ha (18 percent of the total forest area in reporting countries and territories). The proportion of forest in protected areas was 30 percent in Latin America and the Caribbean; 9 percent in North America; and 6 percent in Europe (including the Russian Federation) (FAO, 2020). The area of forests in protected areas increased between 1990 and 2020, albeit with a slowing average annual rate of increase – it was 10.1 million ha in 2000–2010 and 2.8 million ha in 2010–2020.

FRA 2020 collected information on forest management plans, forest ownership and management rights. More than 2 billion ha of forest was estimated to be subject to management plans in 2020, almost half of which was in Europe, particularly the Russian Federation. Less than 25 percent of the forest area in Africa and Latin America and the Caribbean was under management plans in 2020. Globally, the area of forest subject to management plans increased by 233 million ha between 2000 and 2020.

Seventy-three percent of the world's forests was under public ownership in 2020, 22 percent was privately owned, and the ownership of the remainder was categorized as either "unknown" or "other" (the latter mainly comprising forests where ownership is disputed or in transition). Public ownership was predominant in all regions. Latin America and the Caribbean, North America and the Southwest Pacific had the highest proportions of private forests. Globally, the share of publicly owned forests has decreased since 1990 and the area of forest under private ownership has increased.

Public administrations held management rights to 83 percent of the publicly owned forest area globally in 2020. The share of public administration management rights has decreased globally since 1990, with an increasing share of publicly owned forests managed by business entities and institutions and by Indigenous and tribal communities.

2.5 Drivers of deforestation and forest degradation

The drivers of deforestation and forest degradation can be direct or indirect. Direct drivers are identifiable, place-based and visible, and indirect drivers, such as economic, political and cultural factors, are the underlying driving forces that result in direct drivers (IPCC, 2022a).

Examples of direct drivers of deforestation include conversion of forest to cropland, infrastructure or mines. In the case of conversion to cropland, the underlying indirect driver could be an increase in meat consumption, which would increase the demand for and price of soy as feed and therefore incentivize landowners to convert their forests into cropland.

The direct drivers of forest degradation include repeated forest fires and long-term overharvesting, the underlying indirect drivers of which might relate to conflicts over land use (fires) and high demand for charcoal (overharvesting).

The RSS found that, globally, almost 90 percent of the direct drivers of deforestation between 2000 and 2018 were related to agricultural expansion (FAO, 2022c). More than half (52.3 percent) of deforested land was converted to cropland and 37.5 percent was used for livestock grazing. Globally, about 7 percent of deforestation that occurred between 2000–2018 was due to the establishment of oil-palm plantations.

The direct drivers of deforestation varied between regions in the period studied. In Africa and Asia, more than 75 percent of deforestation was driven by cropland expansion; in South America and Oceania, the most important driver was livestock grazing; and, in Europe, land-use conversion was dominated by infrastructure and urban expansion.

The extent of forest degradation is more challenging to quantify due to the lack of commonly agreed criteria for its assessment. For FRA 2020, 58 countries representing 38 percent of the global forest area reported that they monitored the area of degraded forest, although they used varying definitions of degraded forest and few applied quantitative criteria.

At least two recent studies suggest that forest degradation is increasing and that it may surpass the rate of deforestation in some areas (IPCC, 2022a; Matricardi *et al*., 2020; Sedano *et al*., 2021; Lapola, *et al*., 2023). Similarly to deforestation, the direct drivers of forest degradation vary by region: in Africa, charcoal production and woodfuel consumption have been identified as the most important drivers; in Asia and South America, wood extraction is the dominant cause (Hosonuma *et al*., 2012).

2.6 Conclusions

Despite internationally agreed targets to halt deforestation, restore degraded forests and increase forest area (UN, 2015; UN, 2017), deforestation and forest degradation continue. The reduction in the rate of deforestation, and increases in the area of forests under long-term management plans and in protected areas (FAO, 2020), are signs of improvement towards more sustainable land use, but the speed with which the change is happening is insufficient to meet the targets.

The direct drivers of forest loss are mostly related to agricultural expansion, but the underlying factors – or indirect drivers – are complex combinations of demographic, economic, political and other factors. Important indirect drivers include economic growth, increasing demand for agricultural products, including timber, weak governance and institutions, and illegal activities (Kissinger *et al*., 2012).

The world population has more than tripled since the 1950s, and the latest United Nations projections indicate that it could reach 8.5 billion people in 2030, 9.7 billion in 2050 and 10.4 billion in 2100. At the same time, increasing wealth is directing consumption toward more resource-intensive foods, such as meat and dairy (World Resources Institute, 2019). This, combined with climate change, land degradation and biodiversity loss, which could all have negative impacts on the productivity of food systems, is likely to increase demand for land for food production.

Halting deforestation, restoring degraded lands and protecting biodiversity require immediate actions to enable sustainable consumption and production patterns, reduce food loss and waste, develop climate-change-adapted and -mitigating food systems, and decouple human economic activity from environmental degradation.

Chapter 3

State of woodlands and agroforests

3.1 Introduction

The local to global importance of trees outside forests for people and the environment is increasingly acknowledged. Many natural woodlands, such as the Miombo-Mopane woodlands, occupy large areas of drylands globally. Drylands are especially vulnerable to climate change, and maintaining tree diversity in such areas is likely to be crucial for climate resilience (FAO, 2019b). Lessons from dryland woodlands can also inform broader climate-change adaptation and mitigation efforts.

Agroforestry systems cover large areas globally and support many rural livelihoods while also providing ecosystem services (Zomer *et al.,* 2014).[7] FAO's *The State of the World's Forests 2022* (FAO, 2022a) emphasized agroforestry interventions as part of forest and landscape restoration initiatives to support planetary health. The expansion identified the expansion of agroforestry and the restoration of degraded lands was identified as one of three major interrelated tree-associated pathways for supporting resilient economies and environmental recovery.

The focus of this chapter is on trees in natural woodland, termed "other wooded land" (OWL) by FAO for global reporting (FAO, 2023b), and on agroforestry systems. This is a departure from SoW-FGR1 (FAO, 2014a), which did not describe the extent of OWL and agroforestry in detail. The present chapter does not address trees in urban settings, which cover at least 20 million ha globally (FAO, 2020) and provide urban residents with multiple benefits (Kowarik *at al.,* 2019); nor does it address tree orchards and palms (Box 4).

3.2 The role of woodlands and agroforests in managing forest genetic resources

The country submissions for this report indicate that, globally, woodlands and agroforests are important sources of FGR across the four climatic domains, albeit with considerable variation between countries. Canada reported that its woodlands, dominated by wooded wetlands found mainly in the boreal zones, harbour 36 tree species, of which one-quarter is rare deciduous species. Guinea noted that its savannahs host a rich diversity of tree species, which often differ from those found in forests. Finland and Sweden noted the importance of a subspecies of downy birch, *Betula pubescens* subsp. *czerepanovii*, as a keystone species in their subalpine regions.

In their submissions for this report, countries in the tropics and subtropics especially stressed the importance of agroforests – in Sri Lanka, for example, agroforest homegardens cover about 15 percent of the land area. Nevertheless, agroforests are also important in the temperate zone. In Spain, dehesa landscapes represent an important source of genetic resources for some species of oak (*Quercus* spp.) and ash (*Fraxinus* spp.). Argentina reported the existence of more than 22 000 km of shelterbelts, composed

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[7] Agroforestry can be defined as the growing or retention of trees with crops and/or animals (Nair, Kumar and Nair, 2022).

BOX 4
Categorizing the presence of trees outside forests

The Global Forest Resources Assessment (FRA) invites countries to report on trees in the following categories: "forest"; "other wooded land" (OWL); and "other land with tree cover" (FAO, 2023). In the other land with tree cover category, FAO applies the following exclusive subcategories for FRA reporting: "trees in urban settings"; "tree orchards"; "palms"; "agroforestry"; and "other". Domesticated tree crops in the tree orchards and palms subcategories are considered, for reporting purposes, to be plant genetic resources for food and agriculture and their status is reported, therefore, in *The State of the World's Plant Genetic Resources for Food and Agriculture.* Agroforestry is the only subcategory of other land with tree cover covered in the present report.

Source: **FAO.** 2023. *Terms and definitions. FRA 2025*. Forest Resources Assessment Working Paper No. 194. Rome.

primarily of poplars (*Populus* spp.). These shelterbelts are crucial for protecting fruit and vineyard crops from winds, particularly in the Cuyo and Patagonia regions. In addition to their protective functions, the country's shelterbelts produce sawn timber and panels.

Many countries noted that their definitions of woodlands and agroforests differ from those used by FAO for global reporting on forests and other landscapes containing trees (FAO, 2023b). Although many countries provided estimates of woodland area, agroforests are typically less inventoried. For these reasons, several countries noted that better data are needed on woodlands and agroforests, as well as on the FGR found in them. Given that the country reports provided limited information on woodlands and agroforests, the following sections summarize the extent and species composition of these land uses based on available global assessments and other studies.

3.3 Extent of other wooded land and agroforestry systems

Extent of other wooded land

FRA 2020 (FAO, 2020) reported the total global area of OWL in 2020 at 977 million ha, which is about 7 percent of all land and one-quarter of the total area classified as forest.[8] Of the continents, Africa had the largest area (446 million ha), followed by Asia (191 million ha) and South America (147 million ha) (FAO, 2020). China had the largest area of OWL of any country (110 million ha); Argentina and the Russian Federation both had at least 60 million ha; and Canada, Namibia and South Africa all had more than 40 million ha (FAO, 2020). Thus, boreal, temperate, subtropical and tropical regions all have substantial areas of OWL.

The global area of OWL was reported to decline by 31 million ha between 1990 and 2020 (FAO, 2020), due mainly to losses in Africa and South America. In contrast, the area of OWL was reported to increase in Asia and North America over the same period (due partly to changes in reporting). Countries reported land-clearing and fire as threats to OWL, with increased fire frequency linked to climate change a particular concern.

The country reports also indicated challenges in monitoring OWL as part of FRA reporting, with gaps in capacity and capability in many countries. Moreover, some countries have their own classifications for tree cover that do not always fit well with FRA categories used for cross-country compilation (FAO, 2023b).

To improve the reporting of OWL, FAO supports the application of remote sensing and

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[8] Tabulated information for reporting the extent of other wooded land and agroforestry systems is available at https://doi.org/10.5281/zenodo.14700675 (Dawson *et al.*, 2025).

modern digital tools for measurement purposes. The recent RSS (FAO, 2022c) (see Chapter 2), which was carried out in parallel with FRA 2020, involved the participation of hundreds of national experts in interpreting satellite images from hundreds of thousands of sample sites worldwide using the Open Foris Collect Earth Online image analysis platform (Saah *et al.*, 2019). The RSS identified 1.70 billion ha of OWL to 2018 (FAO, 2022c), which is 13 percent of the total global land area, almost double the area reported in FRA 2020 (FAO, 2020). This large discrepancy was not mirrored in the estimates of forest area generated by the two approaches, which were only a few percentage points apart. Rather, it reflects the difficulties countries face in measuring OWL and also differences in the OWL accounting methods they used in reporting to FRA; it also highlights the need for a unified approach for measuring land categories.

In common with FRA 2020, the RSS found that, of the regions, Africa (407 million ha) had the largest extent of OWL, followed by Oceania (370 million ha) and North and Central America and the Caribbean (341 million ha combined) (FAO, 2022b). The survey showed that North and Central America and the Caribbean (considered together) and Oceania have much larger areas of OWL than reported in FRA 2020, reflecting differences among countries in reporting approaches for the FRA.

An earlier FAO-coordinated remote-sensing survey on drylands (FAO, 2019b) also reported on OWL to 2015, including grasslands with tree and shrub cover. That study, which reported the occurrence of drylands on 41 percent of the Earth's land surface, used methods similar to those used in the more recent RSS (FAO, 2022c). It found that OWL accounted for 10 percent of the assessed drylands, with the proportion of OWL higher in semi-arid and arid zones than in hyperarid and dry subhumid zones (FAO, 2019b). In the drylands study, the area of OWL in North and Central America and the Caribbean (considered together) and Oceania was estimated to be high, both in absolute terms and as a proportion of total land area; African drylands also had large areas. Of OWL in drylands, 54 percent was classified as grasslands with shrubs and 39 percent was assessed as grasslands with trees and shrubs. The proportions of coverage by these two vegetation types varied by region, with, for example, grasslands with shrubs making up 77 percent of the OWL in South America and 40 percent in Western and Central Africa (considered together).

Extent of agroforestry systems

FRA 2020 provided data on the extent of land subject to agroforestry practices (FAO, 2020). The estimate of 45 million ha worldwide was based on information provided by 71 countries and so is incomplete, with many countries – such as Brazil and China – known to have large areas of agroforestry not represented in the estimate. The RSS (FAO, 2022b) estimated that, to 2018, 533 million ha of cropland (28 percent of all cropland) and 577 million ha of grassland (21 percent of all grassland) had tree cover greater than 10 percent (as assessed by tree-canopy cover as a percentage of land area). Of the continents, Africa was estimated to have the largest area of cropland with more than 10 percent tree cover (218 million ha), followed by Asia (205 million ha) and Europe (a distant third, at 46 million ha). Africa was also estimated to have the most grassland with more than 10 percent tree cover, at 200 million ha, followed by South America, at 133 million ha, and then by North and Central America and the Caribbean (considered together) and Europe, both at 92 million ha. The difference in rankings of Asia and South America for trees in cropland and grassland reflect the higher prevalence of pastureland-associated agroforestry in the latter region and hence the different management systems used for production and resource conservation purposes.

Zomer *et al.* (2014) used remote-sensing data to estimate the extent of agroforestry globally by aggregating tree-cover and land-use datasets to a resolution of 1 km^2 and comparing the global area of agroforestry in 2000 and 2010.[9] They estimated that about 1 billion ha of recognized agricultural land globally had more than 10 percent tree cover in 2010, equating to about 43 percent of all farmed land, up from 40 percent of all farmed land in 2000. The estimate of 1 billion ha is similar to the combined area of cropland and grassland with more than 10 percent tree cover estimated by the RSS (FAO, 2022c), at 1.11 billion ha (see above). According to Zomer *et al*. (2014), regions where large areas of farmland have much more than 10 percent tree cover include Southeast Asia, Central America and coastal West Africa. Regions where large areas of agricultural land have some tree cover, but less than 10 percent, include Australia, the Sahelian countries and Türkiye.

Using a working definition of agroforestry of at least 10 percent of tree cover in agricultural land, Zomer *et al.* (2014) estimated that Asia (excluding Western Asia, which was reported separately, in combination with North Africa) had the largest area of agroforestry land use in 2010, at 330 million ha, followed by South America, at 255 million ha. Estimates for Africa were lower than those generated by the RSS (FAO, 2022c), in part because Zomer *et al.* reported on sub-Saharan Africa rather than all of Africa. According to Zomer *et al.* (2014), agroforestry as a percent of total agricultural land was 95 percent in Central America, 77 percent in Southeast Asia and 53 percent in South America.

Zomer *et al.* (2014) explored how change in agroforestry area varied across regions between 2000 and 2010. South America was estimated to have the largest percentage increase in agricultural land covered by agroforestry (up from 53.0 percent to 65.6 percent). Increases were also observed in Africa, Asia, Oceania and North and Central America and the Caribbean, and there was no change in Europe. There were differences within regions, too: in Asia, for example, there was an overall increase in agroforestry of 2.4 percent between 2000 to 2010, with relatively large increases in South Asia (6.7 percent) and East Asia (4.9 percent) and a decline of 2.9 percent in Northern and Central Asia (considered as a single region).

Zomer *et al.* (2014) combined tree-cover maps with a map of human population density to estimate how many people lived in agricultural lands with greater than 10 percent tree cover. Their estimate of 800 million people in 2010 is a substantial proportion of the world's rural population, and there were especially large concentrations of people living near or in these "treed" agricultural lands in parts of Africa and Asia (the association of people with treed agricultural lands was confirmed by a separate analysis – FAO, 2022a – that used more-recent data on human population density). This finding makes clear the importance of involving communities in the design of agroforestry-based management interventions that support conservation. Later studies (Zomer *et al*. 2016; 2022) explored the value of defined agroforestry areas for climate-change mitigation in terms of global biomass carbon stocks in agricultural land. Those studies estimated that current carbon stocks in agricultural lands subject to agroforestry are large and that even incremental changes in agroforestry practices could result in further large carbon capture, illustrating the value of managing such lands for multiple functions.

3.4 Composition of trees in other wooded land and agroforestry systems

Systematic inventories repeated over time at the same location (known as longitudinal surveys) are a standard approach for studying tree species composition and change. The OWL and agroforestry land-cover categories, however, have received less inventory attention than forests, especially in comparative (cross-location) studies, which are needed for the assessment of conservation priorities.

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[9] No equivalent exploration of agroforestry land area has been made using more recent datasets.

Composition of other wooded land

In the absence of systematic, comprehensive cross-site inventories of OWL globally, more opportunistically obtained point location data on trees, as recorded in global databases such as the Global Biodiversity Information Facility (GBIF, 2022), can be useful for building a picture of how tree species composition varies between geo-referenced locations. In a recent study, Kindt (2023) used point location data for more than 48 000 tree species globally in forests and woodlands to model potential species distributions and generate species-richness estimates for both baseline (current) and potential future anthropic climates. The study modelled higher tree species diversity in humid tropical forests than woodlands, as expected, but indicated substantial diversity in some woodlands, too, in agreement with existing field inventories. The geographic coverage of the point location data is patchy globally, however, with some regions and land-use types better represented than others.

Another way to obtain an overview of tree species composition in woodlands is from high-resolution potential natural vegetation maps focused on the tree component of vegetation landscapes. Although such maps are not yet widely available globally, important regional exceptions exist in which higher-resolution data allow cross-location comparisons. In eastern Africa, ecologists combined national vegetation maps to produce the cross-country vegetationmap4africa (van Breugel *et al.*, 2015), which has been used to characterize landscapes and regionally prioritize important tree species for woodland restoration. The same regional map has been used with ecological niche modelling and multiple tree molecular genetic diversity datasets to plan tree-based conservation and restoration activities in eastern Africa that more fully account for anthropogenic climate change. A similar approach could be used elsewhere if relevant genetic datasets can be assembled and standardized (Dawson *et al.*, 2017).

Composition of agroforestry systems

Diverse agroforestry systems exist globally, with differing compositional characteristics, levels of species richness, and management approaches. Shifting cultivation, silvopastoralism and parklands are examples of extensive agroforestry systems; homegardens, smallholder commodity cropping and alley cropping are more intensive. A feature of agroforestry systems is the interactions between components, such as trees and annual crops, that are often (but not exclusively) positive for livelihoods and the environment (Reed *et al*., 2017).

Cornelius *et al*. (2019) described a range of agroforestry systems. Examples are traditional parkland systems in the Sahelian zone of West Africa, which are mixed crop–tree–shrub–livestock assemblages derived from savannah ecosystems; wood-producing commercial systems in India and Viet Nam, which use only a few tree species; the highly diverse homegardens in South Asia and South America that provide tree foods; the species-rich *cabrucas* in Brazil, which produce cacao in native forests; the *dehesa* in Spain, which consist of oak trees with livestock grazing underneath; and shelterbelt systems in North America.

Tree species richness varies greatly among agroforestry systems, from 1–2 species to several hundred species. The relatively small number of systematic inventories of the tree species used in agroforestry have focused on more-biodiverse systems because these are the most interesting for tree conservation management. A literature review of agroforestry tree inventories carried out for this report (Table 6) found that inventory studies with properly described tree species sampling and recording have been undertaken in 20 countries (all of which are tropical or subtropical); the number of tree species counted ranged from 41 to 424.

A full analysis of inventory findings requires a more detailed consideration of sampling approaches than is possible in current reporting (but see legend to Table 6). Nevertheless, it seems clear that many agroforests in the tropics and subtropics have high tree species richness and that,

TABLE 6

Findings of a literature review of tree species richness inventories in agroforestry systems

Country	Agroforestry system	Inventory results	Reference
Côte d'Ivoire	Commodity crop	41 tree species	Herzog (1994)
Central African Republic	Parkland	47 tree species	Kpolita *et al.* (2022)
United Republic of Tanzania	Home garden	53 tree species	O'kting'ati *et al.* (1984)
Madagascar	Commodity crop	56 woody plant species	Danthu *et al.* (2022)
Senegal	Parkland	63 tree species	Camara *et al.* (2019)
Ethiopia	Commodity crop	71 woody plant species	Zewdie *et al.* (2022)
Sri Lanka	Home garden	85 tree species	Martin *et al.* (2019)
India	Home garden	87 tree species	Das and Das (2005)
Guinea	Commodity crop	94 species	Correia *et al.* (2010)
Panama	Silvopasture	99 tree species	Garen *et al.* (2011)
Burkina Faso	Parkland	106 tree species	Bayala *et al.* (2011)
Ghana	Commodity crop	106 shade tree species	Graefe *et al.* (2017)
Mexico	Commodity crop	107 tree species	López-Gómez, Williams-Linera & Manson (2008)
Indonesia	Home garden	>120 tree species	Marjokorpi & Ruokolainen (2003)
El Salvador	Commodity crop	123 tree species	Méndez, Gliessman & Gilbert (2007)
China	Commodity crop	155 shade trees species	Rigal, Vaast & Xu (2018)
Costa Rica	Silvopasture	190 tree species	Harvey & Haber (1998)
Cameroon	Commodity crop	206 tree species	Sonwa *et al.* (2007)
Brazil	Commodity crop	293 tree species	Sambuichi & Haridasan (2007)
Kenya	Home garden	424 woody plant species	Kehlenbeck *et al.* (2011)

Notes: The systematic review of the literature involved the screening (on 8 May 2022) of titles and abstracts listed in Web of Science and Scopus databases for search terms related to "agroforestry", "biodiversity" and "inventory". From an initial set of 150 potentially relevant studies, full-text screening identified 20 countries that had inventories on the total number of tree/woody perennial species in agroforestry systems, along with sufficient information on the sampling approach to be able to interpret findings. Sometimes, more than one study was identified in a country, but the table shows only a single inventory per country for illustrative purposes. Studies listed in the table are ordered from lowest to highest in tree species richness. Note that the interpretation of inventory findings requires that the sampling approach for each inventory is properly understood in terms of the scale of sampling (e.g. number of plots, plot areas and distance between plots). This is because species richness can accumulate quickly when sampling is expanded for systems that contain substantial diversity.
Source: Authors' own elaboration. See References for the details of cited publications

although this richness is contributed primarily by native trees, introduced trees often dominate on a "trees per hectare" basis. Moreover, several of the reported systems showed evidence of a transition over time to less-diverse states.

Agroforestry systems can play important roles in tree species conservation, but with caveats. First, the low density of native tree species found in many agroforestry systems is problematic, given that these trees could be at risk from changes in farmer practices. Such trees may also face inherent biological risks from inbreeding and limited seed set, depending on how the systems are managed, the overall species assemblage, and how population density compares with the trees in their natural state (Dawson *et al.*, 2013). A second caveat on the role of agroforestry systems in tree species conservation is the tendency to become less diverse, which suggests that, without active intervention, the conservation value of agroforests will reduce over time. An important intervention would be the targeted planting at scale of high-conservation-value trees in agroforestry systems, which could be assisted by improving the access of agroforestry managers to the germplasm of such trees (Lillesø *et al.*, 2018; Graudal *et al.*, 2021).

3.5 Management of other wooded land and agroforestry systems

Determining the dynamics of treed landscapes in other wooded land and agroforestry in different regions globally is not straightforward. Large variations exist in the proportions of tree cover, absolute tree cover, tree-cover change over time and other parameters, requiring tailored management interventions that support conservation in different locations.

In agroforestry, a particular issue to consider is the relationship between changes in the area of agriculture and forests. Globally, almost 90 percent of the reported deforestation between 2000 and 2018 (a total area of 93 million ha) was due to agricultural expansion (FAO, 2022c; see also Chapter 1), with the specific contributing factors varying among the regions. In Africa and Asia, the biggest reported contributor was cropland expansion; in South America it was the expansion of livestock grazing land. In different regions, therefore, different interventions at the farm level are required to support natural forest conservation and enhance the value of agroforestry in maintaining tree species and their genetic resources.

Where cropland expansion is associated with small-scale farming, as is often the case in Africa, opportunities for retaining tree cover and associated biodiversity in agroforestry settings are likely to be greater than in areas where large-scale farming prevails. This is because smallholders often have greater need to diversify their farms for their own use of tree and crop products; their farms may lack the mechanization often associated with farming landscape simplification; and they may be more willing to tolerate a certain amount of "redundant" diversity (Dawson *et al.*, 2019). The options for on-farm conservation may be more limited where larger-scale farming expansion is associated with the establishment of monoculture tree-commodity crops, especially oil palm in Asia and commercial cattle ranching coupled with soybean production in South America (FAO and UNEP, 2020). Countering the ability of smallholder-based agroforestry to support tree conservation is the observation that countries in which small farmers predominate often perform relatively poorly on indicators related to the enabling conditions for tree-cover restoration action (Shyamsundar *et al.*, 2022). Shyamsundar *et al.* (2022) suggested that partnering with farmers and prioritizing their preferences, reducing uncertainties, strengthening markets and mobilizing innovative financing are key requirements for progress towards tree cover restoration; at the same time, introducing policies and practices that specifically support biodiverse tree-planting is key (Graudal *et al.*, 2021).

3.6 Conclusions

Globally, OWL and agroforests are important sources of FGR, but this importance varies considerably between countries. The management of FGR in OWL and agroforests would benefit from better data, which could be achieved with improvements in international reporting on these land-use types.

Reporting on OWL requires standardization; for agroforests, efforts are needed to integrate this land use more fully into FRA reporting by countries (similar efforts are also required for reporting on other subcategories in FAO's "other land with tree cover" category) (de Foresta, 2017). Obtaining more data on agroforestry is especially important for those non-reporting countries that remote sensing indicates have large areas of agroforestry. In 2022, the Committee on Forestry recommended that FAO conduct a global assessment of the status and scaling-up potential of agroforestry to update the FRA categories covering production systems that integrate trees and forests. In response to this recommendation, FAO has initiated a global agroforestry monitoring assessment, which is planned for publication in 2025. Rosenstock *et al.* (2019) attributed the absence of adequate national reporting on agroforestry to a combination of institutional, technical and financial challenges and suggested that more access to remote-sensing methods, the use of consistent definitions, and the establishment of better practices for cross-institutional collaboration are among the measures needed to drive reporting improvements.

Recent advances in remote sensing using high-spatial-resolution satellite data and advanced machine learning offer new means for studying the extent and nature of trees outside of forests, especially where tree densities are low and where different land-use types are being compared. For example, advanced remote-sensing methods can show a higher presence of trees than indicated initially in relatively low-density landscapes (Brandt *et al.*, 2020). The ultimate target of these new methods is to produce accurate information on all trees outside forests, everywhere. Advanced remote-sensing methods will increasingly be able to distinguish between tree species (Lu *et al.*, 2022) but, despite such advances, field surveys will likely always be needed to assess floral assemblages and to understand the drivers of change (implying a continued need to maintain and develop the human resources required to do this work).

The most important advances in the development of context-specific sustainable management approaches for OWL and agroforestry systems will come from a better understanding of the functionality of landscapes at the local, national and regional scales, for which estimates of tree cover and land-use type, and information on species composition, are only a starting point. Such understanding is especially important for managing landscapes in the face of rising environmental challenges (Aleman and Staver, 2018; Charles-Dominique *et al.,* 2015).

Chapter 4

State of diversity of tree and other woody plant species

4.1 Introduction

Trees first appeared over 300 million years ago, and woodiness has since evolved multiple times in plant families in many taxonomic groups (FitzJohn *et al.*, 2014; Kenrick and Crane, 1997). Today's global tree diversity reflects this long history, with species evolving and adapting to highly varied conditions.

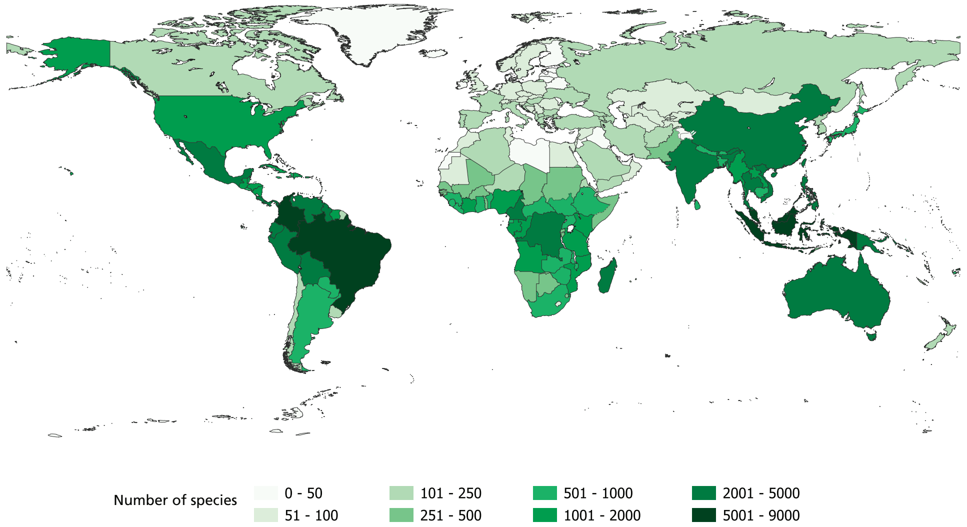
The palm family occupies a somewhat ambiguous position among woody plants. Around 40 percent of the approximately 2 500 species of palm produce stems ≥10 cm in diameter at 1.3 m and are readily interpreted as trees (Muscarella *et al*., 2020), but they do not produce typical wood or display typical tree architecture, being monocotyledonous and therefore lacking secondary growth (Tomlinson, 2006). In practice, palms display a wide range of growth forms, including trees, short-stemmed and stemless shrubs, prostrate shrubs with creeping stems, and climbers (or rattans) (Dransfield *et al*., 2008). In all growth forms, stems can be solitary, or they may sucker to form clumps of clustered stems. Although many of these species are encompassed within the broad definition of trees (e.g. that used by the IUCN's Global Tree Specialist Group – see below) and are likely to be accounted for within the general discussion of trees below, the more than 500 climbing species tend to be treated as lianas (see below). Regardless of the semantics, palms have an exceptionally long history, extending back more than 100 million years, and have been crucial elements of forest ecosystems since that time (Couvreur *et al*., 2011).

Bamboos, which originated at least 20 million years ago, constitute a major group of woody species in the grass family Poaceae, subfamily Bambusoideae. They are the only major lineage of grasses to have evolved in association with forests (Clark, Londoño and Ruiz-Sanchez, 2015; Guo *et al*., 2019). Most bamboos grow along forest edges or in gaps, but some occur in forest understories and others have adapted to open habitats such as savannahs and high-elevation grasslands. Like palms, bamboos lack secondary growth and their woodiness is the result of primary growth followed by lignification.

The IUCN Red List of Threatened Species (IUCN, 2024) is the most widely used system to assess the probability of extinction of species. Five criteria are used for evaluating whether a species is Critically Endangered, Endangered or Vulnerable: (A) reduction in population size; (B) geographic range; (C) small population size and decline; (D) very small or restricted population; and (E) quantitative analysis of the probability of extinction in the wild (IUCN, 2012). The criteria are based on quantitative thresholds; if the species is within these thresholds, it is assessed as threatened and therefore at high risk of going extinct. If a species does not qualify for a threatened category now but is likely to do so soon, or if a species is close to qualifying for a threatened category, it is assessed as Near Threatened. Widespread and abundant species are classified as Least Concern, and those species with inadequate information to complete an assessment are evaluated as Data Deficient. Extinct and Extinct in the Wild are categories

FIGURE 7

Tree species richness based on the natural distributions of all tree species



Note: Refer to the disclaimer on page ii for the names and boundaries used in this map. Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties. Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined.
Source: Authors' own elaboration using data from: BGCI. 2024a. *GlobalTreeSearch online database*. Richmond, UK. Cited 30 May 2024. www.bgci.org

used for species that have been extirpated. A detailed methodology is presented in the IUCN Red List guidelines (IUCN Standards and Petitions Committee, 2024). Assessments are complemented by maps and supporting information, including on distribution, habitat, ecology, population, use, threats and conservation actions.

4.2 Diversity of tree species

Number of tree species

Previous estimates of the number of tree species globally have ranged from 45 000 to 100 000 (Beech *et al.*, 2017; Cazzolla Gatti *et al.*, 2022; Fine and Ree, 2006; Oldfield, Lusty and MacKinven, 1998; Tudge 2006). Hunt (1996) estimated 21 000 tree species in temperate regions and Slik *et al.* (2015) estimated 40 000–53 000 in the tropics. GlobalTreeSearch is the first global database of tree species and their natural country distributions; it was published in 2017 (Beech *et al.*, 2017) and has continued to be refined since (BGCI, 2024a). Information in GlobalTreeSearch is derived from plant databases, scientific references and tree experts and kept up-to-date to reflect changes in taxonomy, nomenclature and life form, as well as known natural distributions of species. It is based on the definition by IUCN's Species Survival Committee Global Tree Specialist Group, which defines a tree as a woody plant with usually a single stem growing to a height of at least 2 m or, if multi-stemmed, with at least one vertical stem 5 cm in diameter at breast height. Plant taxonomists and botanists continue to catalogue the diversity of tree species and to seek understanding of the relationships between species groups. Some areas of the world are poorly known botanically, and many taxa are undescribed, especially in Latin America (Cazzolla Gatti, 2022).

As compiled in GlobalTreeSearch, there are 57 681 named tree species globally, as of May 2024 (BGCI, 2024a). These species occur in

266 taxonomic plant families and 4 188 plant genera, including tree-like palms in the family Arecaceae. More than 45 percent (26 121 tree species) occur in just ten taxonomic families. The family with the most tree species is Fabaceae, with 5 098, followed by Rubiaceae (4 417) and Myrtaceae (4 129). The most diverse tree genera are *Syzygium* (1 084 species), *Eugenia* (839 species), *Diospyros* (758 species), *Eucalyptus* (723 species) and *Ficus* (693 species).

Distribution of tree species

Except for the extreme polar regions and at the Earth's highest altitudes, trees are found in all parts of the world. Tree diversity is not evenly distributed, however, with species richness (i.e. the number of species) varying between regions. Tree diversity is higher in the tropics and subtropics than in most temperate and boreal regions. For example, Europe has 465 native tree species (IUCN, 2024; Rivers *et al.*, 2019) and North America (including Hawaii) has 1 230, but Africa (9 388 native tree species), Latin America and the Caribbean (16 581) and Asia (18 779) each have an order of magnitude more (BGCI, 2024a).[10]

Some tree species are naturally widespread, such as tallow wood (*Ximenia americana*), which occurs naturally in 96 countries. Most, however, have much more restricted distributions: for example, 58 percent of tree species are single-country endemics (BGCI, 2024a).

The country with the most diverse tree flora is Brazil, at 8 758 tree species, followed by Colombia (5 928) and Indonesia (5 920) (Figure 7; Table 7) (BGCI, 2024a). The countries and territories with the highest numbers of endemic tree species (i.e. species confined to a single country or territory) are (in descending order, by number of endemic tree species) Brazil, Madagascar, Australia, China, Mexico, Indonesia, Malaysia, Papua New Guinea, the Philippines and New Caledonia. Geographically isolated countries and territories such as Madagascar, New Caledonia and New Zealand have the largest proportion of endemic tree species, with more than 90 percent of their tree species occurring naturally nowhere else.

Diversity and distribution of useful tree species

Trees play major functional roles in the world's terrestrial ecosystems and provide billions of people with a wide range of socioeconomic benefits (Rivers *et al.*, 2022). The Center for International Forestry Research and World Agroforestry (CIFOR–ICRAF) has developed the GlobalUsefulNativeTrees database (GlobUNT) (Kindt *et al.*, 2023) by combining native-country distribution data from GlobalTreeSearch with information on ten categories of documented human usage available in the World Checklist of Useful Plant Species (WCUPS) (Diazgranados *et al.*, 2020). GlobUNT contains 14 014 useful tree species, which is roughly one-quarter of the tree species in GlobalTreeSearch and one-third of the plant species in WCUPS.

The 20 genera with the highest number of tree species in GlobUNT are *Ficus* (287), *Syzygium* (189), *Diospyros* (184), *Eucalyptus* (155), *Quercus* (117), *Terminalia* (99), *Acacia* (98), *Elaeocarpus* (96), *Garcinia* (96), *Croton* (94), *Prunus* (93), *Coffea* (90), *Pinus* (87), *Salix* (82), *Macaranga* (75), *Dombeya* (74), *Shorea* (74), *Commiphora* (73), *Magnolia* (69) and *Ilex* (67). According to GlobUNT, 9 261 tree species are used as materials and 8 283 are used as medicines. Other documented uses include environmental functions (3 317 species), human food (3 310), fuel (2 162), gene sources (1 552), animal food (1 494), social uses (1 396), poisons (1 109) and insect food (712).

Indonesia and Malaysia have the largest numbers of documented useful tree species, followed by Brazil, China, India and Thailand. Other countries with high numbers of useful tree species are Colombia, the Democratic Republic of the Congo, Papua New Guinea and Thailand. The GlobUNT data indicate that the proportion of native tree species with identified uses is higher in Africa and Asia than in South America (Kindt *et al.*, 2023).

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[10] These regions are defined in BGCI (2024a); they may differ from the regions used elsewhere in this report.

TABLE 7

Tree species recorded in GlobalTreeSearch and GlobalUsefulNativeTrees for the 23 countries with more than 2 000 tree species in GlobalTreeSearch

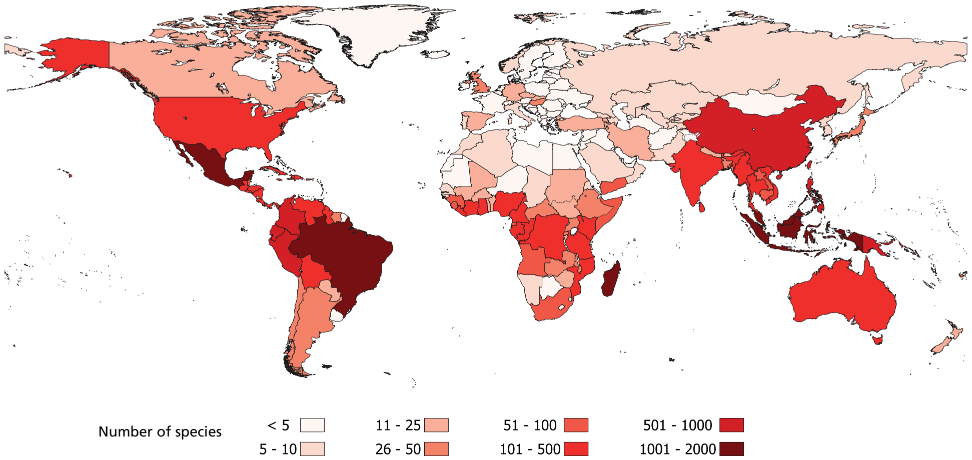
Country	Total number of tree species	Total number of endemic tree species	Total number of useful tree species
Brazil	8 775	4 088	1 772
Colombia	6 045	1 150	1 342
Indonesia	5 924	1 503	2 724
Malaysia	5 293	1 389	2 115
Venezuela, Bolivarian Republic of	4 725	785	1 202
China	4 531	2 086	1 594
Peru	4 608	772	1 106
Ecuador	3 841	573	929
Mexico	3 744	1 579	1 118
Australia	3 241	2 721	954
Madagascar	3 204	2 973	597
Bolivia, Plurinational State of	3 042	288	1 058
Papua New Guinea	2 876	1 287	1 361
Panama	2 646	331	733
Viet Nam	2 621	465	1 205
India	2 587	674	1 591
Costa Rica	2 560	332	711
Thailand	2 554	221	1 478
Philippines	2 482	1 223	1 041
Guyana	2 258	128	775
Cameroon	2 041	240	1 155
Democratic Republic of the Congo	2 016	170	1 228

Sources: BGCI. 2024. GlobalTreeSearch online database. Richmond, UK. [Cited 30 May 2024]. www.bgci. Kindt, R., Graudal, L., Lillesø, J-P., Pedercini, F., Smith, P. & Jamnadass, R. 2024. GlobalUsefulNativeTrees: country-specific selections of native tree species for forest landscape restoration and biodiverse plantings. [Cited 10 May 2024]. https://patspo.shinyapps.io/GlobalUsefulTrees

State of trees

State of the World's Trees (BGCI, 2021) provided a global overview of the risk of extinction for trees based on the Global Tree Assessment, an initiative to carry out threat assessments for all tree species. The Global Tree Assessment, which is coordinated by BGCI and the Global Trees Specialist Group, began in 2015 in recognition of the need to make more information available on tree species to inform conservation decisions. Information was compiled using IUCN Red List assessments and other assessments (e.g. national assessments, flora accounts and scientific papers). Of all known tree species, 142 (0.2 percent) were classified as extinct; 17 510 (30 percent) were classified as threatened; and 7 700 (13.2 percent)

FIGURE 8
Number of threatened tree species, by country/territory



Note: Refer to the disclaimer on page ii for the names and boundaries used in this map. Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties. Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined.
Source: Authors' own elaboration using data from: BGCI. 2024a. GlobalTreeSearch online database. Richmond, UK. [Cited 30 May 2024]. www.bgci.org

were assessed as Data Deficient (many of these are known only from small, relatively unexplored areas); the remainder were assessed as either Least Concern, Near Threatened or Not Evaluated (BGCI, 2021).

Nearly every country has threatened tree species (Figure 8), with the distribution of such species showing a similar pattern globally to that for species richness (see Figure 7). The megadiverse countries of Brazil, China, Colombia and Indonesia have large numbers of tree species and threatened tree species; Madagascar also stands out for its large number of threatened trees (Beech *et al.*, 2021). The pattern differs in the ratio of threatened species to total tree diversity. On average, 11 percent of countries' tree species are threatened, with the highest percentages in Saint Helena (69 percent, n=11), Madagascar (59 percent, n=1 842) and Mauritius (57 percent, n=154). Of the 15 countries and territories with the highest percentages of threatened tree species, all except Chile are islands (BGCI, 2021).

Monitoring tree diversity and conservation actions

The GlobalTree Portal is a new tool for monitoring tree species' distributions, threats and conservation actions (Beech, Hills and Rivers, 2022; BGCI, 2024b) at the species, country and global levels. The data are obtained from the Global Tree Assessment and BGCI's databases (i.e. GlobalTreeSearch, ThreatSearch, PlantSearch and GardenSearch).

As of May 2024, 17 769 (31 percent) of the known tree species were found in *ex situ* collections (i.e. botanic gardens, arboreta or seed banks). Of these, 12 132 species were conserved *ex situ* in their country of origin and 13 571 species were conserved outside their country of origin (BGCI, 2024b). Conversely, 40 015 species were not found in these *ex situ* collections. A total of 34 029 tree species (59 percent of all known tree species) occurred in at least one protected area (BGCI, 2024b).

FIGURE 9
Global distribution of woody bamboos

Note: Refer to the disclaimer on page ii for the names and boundaries used in this map.
Source: Authors' own elaboration using data from: Bamboo Biodiversity. 2023. [Cited 15 February 2023]. https://www.eeob.iastate.edu/research/bamboo/maps.html

4.3 Diversity of woody bamboos

Number and distribution of woody bamboo species

There are 1 729 known bamboo species worldwide in 130 genera, most of which (1 596 species in 106 genera) are woody (Vorontsova *et al.*, 2016; POWO, 2021). Bamboo classification and terminology recently underwent significant changes, and woody bamboos are now defined by their common evolutionary origin and placement in the subfamily Bambusoideae tribe Arundinarieae (temperate woody bamboos) and tribe Bambuseae (tropical woody bamboos). Certain other superficially similar groups were previously classified as bamboos or are frequently confused with bamboos, including reeds (*Phragmites* and *Arundo*) and ancient forest grasses (e.g. *Anomochloa*, *Puelia* and *Guaduella*). Bambusoideae tribe Olyreae (herbaceous bamboos) are bamboos but are not woody (Kellogg, 2015).

Woody bamboos are rhizomatous perennials with woody culms, culm leaves that are distinct from the ordinary pseudopetiolate foliage leaves, foliage leaves with both inner and outer ligules, and complex branching, with usually more than one branch originating at each culm node. Woody bamboos occupy a broad range of environments, largely in tropical to warm-temperate ecosystems and to a lesser extent in cool- to cold-temperate regions (Clark, Londoño and Ruiz-Sanchez, 2015; Kellogg, 2015). Figure 9 shows the global distribution of woody bamboos.

Woody bamboos are known for cyclical or gregarious flowering, in which most or all the populations of a given species flower at the same time (every 10–120 years); frequently, all die after seed is produced, often with profound consequences for local ecosystems (e.g. Janzen, 1976; Singleton *et al.*, 2010; Carvalho *et al*. 2013).

The drivers behind this unusual flowering are not understood, but it is known that different bamboo lineages evolved at different rates and that those with the longest flowering cycles are evolving very slowly (Ma *et al*., 2017).

Temperate woody bamboos

Temperate woody bamboos, comprising approximately 600 species, represent more than one-third of the world's woody-bamboo diversity. With their greater tolerance of cold, this is the group commonly seen growing naturally in Eastern Asia and North America, as well as on tropical mountains. They are also widely cultivated in Europe and North America. The majority are "running bamboos" with leptomorph rhizomes, where the apical meristem of the rhizome continues growing laterally while axillary meristems turn upwards to form culms. The most notable genus is *Phyllostachys*, with 51 species, including moso bamboo (*Phyllostachys edulis*), which is grown for building materials and edible bamboo shoots (Lucas, 2013; Dixon and Gibson, 2014).

Paleotropical woody bamboos

Paleotropical woody bamboos are found in tropical Asia, Africa and Madagascar and consist of approximately 560 species. Some produce fleshy fruits, including the spectacular pear-like fruits of muli bamboo (*Melocanna baccifera*). The most notable and iconic genera are the widespread *Bambusa*, with around 100 species, *Gigantochloa* with 63 species, and *Dendrocalamus* with 41 species, including the world's tallest bamboos. Many species of these three genera are widely cultivated in warmer parts of the world.

Neotropical woody bamboos

Neotropical woody bamboos, which comprise approximately 450 species, are morphologically similar to the paleotropical bamboos except that they are tetraploid. This is the least-well-documented group of woody bamboos, despite their diversity and great ecological significance in Central and South America. *Chusquea* is the largest genus of woody bamboos, with just over 200 species, and it exhibits high rates of morphological diversification in multiple habitats.

Uses of bamboos

Bamboos are commonly known as the "plant of a thousand uses" (Farrelly, 1984). The woody culms are used, for example, for construction (e.g. houses and bridges); furniture; cooking vessels (especially for rice); household items; basketry; many types of handicrafts; musical instruments; charcoal; paper pulp; and poles. The young shoots of many species are edible, and many species are used in traditional medicine. In more-processed forms, culms are used to make laminate, rayon and flooring. Both temperate and tropical woody bamboos are grown widely for landscaping purposes, as specimen plants and as hedges, privacy screens and windbreaks. Taking advantage of the rhizomatous growth of woody bamboos, some species are planted for erosion control and the reclamation of disturbed areas.

According to Diazgranados *et al.* (2020), only 195 woody bamboo species (12 percent of all woody bamboo species) have documented uses, although this number is likely to be an underestimate. Of the 195 species, 116 (60 percent) have multiple uses. Widely cultivated bamboos for commercial and environmental purposes are primarily in the *Bambusa*, *Dendrocalamus*, *Gigantochloa* and *Phyllostachys* genera, as well as *Guadua angustifolia* and *Melocanna baccifera* (Benton, 2015; Cusack, 1999; Diazgranados *et al.*, 2020; Dransfield and Widjaja, 1995; Lucas, 2013 and pers. comm., 2022; R. Saporito, pers. comm., 2022). Some woody bamboo species in *Bambusa, Dendrocalamus, Gigantochloa, ×Phyllosasa* (*Hibanobambusa*) and *Semiarundinaria* are known only from cultivation, with no record of their native origin (Dransfield and Widjaja, 1995; Ohrnberger, 1999).

A total of 232 bamboo species have been recorded as introduced beyond their native ranges, and 12 species have been found to be invasive, with *Bambusa* and *Phyllostachys* proportionally the most likely to be both introduced and invasive (Canavan *et al.*, 2016).

Bambusa vulgaris and *Phyllostachys aurea* have invaded the most areas worldwide (Canavan *et al.*, 2016).

Because bamboos produce seeds infrequently, and these seeds lose viability quickly (Durai and Trinh, 2019), the conservation and use of bamboo genetic resources is challenging. Woody bamboos are typically propagated using cuttings or through layering and rhizome separation (Durai and Trinh, 2019). Their cultivation often requires specialized techniques or species-specific knowledge (Banik, 2015; INBAR, 2023), and micropropagation is used for some commercially cultivated taxa (Mudoi *et al.*, 2013; Banik, 2015; Yuan *et al.*, 2017). Special attention should be given to genetic diversity in the planting stock produced using these propagation techniques. A wide array of insect pests and fungal and viral diseases can cause serious damage to cultivated bamboos (Shu and Wang, 2015), reinforcing the need to maintain genetic diversity.

Bamboo conservation

Because bamboos are associated primarily with forest habitats, deforestation is likely the largest threat to their diversity, but good data are lacking. Most woody bamboos are light-tolerant if not sun-seeking, and some species (e.g. *Chusquea* spp. in the Andes in South America) expand their ranges and biomass to occupy disturbed areas and gaps (Judziewicz *et al.*, 1999). Some bamboos are fire-adapted (e.g. *Actinocladum verticillatum* and *Guadua paniculata* in the savannahs of South America), but most appear to be susceptible to repeated burning. Woody-bamboo diversity is largely associated with mountain systems (Clark, Londoño and Ruiz-Sanchez, 2015), and global warming may therefore pose a threat as elevational ranges move upward.

The native distributions of bamboos appear to reflect the same diversity patterns as in other clades of organisms; that is, relatively few species are common and widespread, a moderate number are fairly common, and the vast majority are rare (Enquist *et al.*, 2019). Few woody bamboos have been assessed for the IUCN Red List, however; for the most part, data are available only for newly described or newly revised taxa (e.g. Attigala, Kaththriarachchi and Clark, 2016; Vidal *et al.*, 2023). Some *ex situ* conservation efforts have been made in the Americas, mainly Mexico (e.g. the Francisco Javier Clavijero Botanical Garden near Xalapa, Veracruz, which is Mexico's national bamboo collection) and Colombia (e.g. the *Guadua* living germplasm collection at the Juan María Céspedes Botanical Garden near Tuluá, Valle del Cauca). Some botanic gardens in India (e.g. the Forest Research Institute Botanical Garden in Dehra Dun, Uttarkhand), China (e.g. the Xishuangbanna Tropical Bamboo Garden, Yunnan Province) and Indonesia (see Widjaja, 2019) have significant Asiatic bamboo collections. Almost all living bamboo collections are located below 1 500 m in elevation, meaning that much of the diversity of bamboo species in high tropical elevations is not well-represented in *ex situ* collections. Existing national parks and reserves in bamboo-rich countries nominally protect bamboo diversity across its elevational ranges, but enforcement varies and climate change is likely to disproportionately affect higher elevations.

Many other organisms are associated with bamboo in its natural habitats, including fungi, insects and vertebrates (the latter including bamboo specialists such as pandas and certain lemurs) (Judziewicz *et al.*, 1999; Paudyal *et al.*, 2022). Although many fungal and insect species are known to use bamboo as a substrate or to eat it, they are not typically problematic for bamboos in stable natural systems, and they contribute to the biodiversity of natural bamboo stands (Shu and Wang, 2015). As the effects of climate change intensify, however, previously relatively benign fungi and insects may emerge as pests or diseases.

4.4 Diversity of rattans

Rattans are spiny, climbing palms that belong to the Calamoideae, one of five subfamilies currently accepted in palms. The 486 species are distributed among eight genera – *Calamus*

(416 species), *Plectocomia* (14), *Plectocomiopsis* (6), *Myrialepis* (1), *Korthalsia* (27), *Laccoserma* (11), *Eremospatha* (7) and *Oncocalamus* (4) (Dransfield *et al*., 2008; POWO, 2024). Some species of *Calamus* are non-climbers, forming stemless or short-stemmed shrubs, but these undoubtedly evolved from climbing ancestors. A further 28 species of palms in subfamily Arecoideae also produce climbers; although technically not rattans, they are remarkably rattan-like (Vorontsova *et al*., 2016). All 24 species of *Desmoncus*, a coconut relative, are spiny climbers with close morphological similarities to some of the rattan genera. Two species in each of the genera *Dypsis* and *Chamaedorea* are climbers, whereas the many remaining species (107 and 106 species in total, respectively; POWO, 2024) are not.

All climbing palms are passive climbers, meaning they do not actively twine or use twining tendrils. All produce elongated stems (relative to non-climbing palms) that can be partially self-supporting due to the stiffening properties of tubular leaf sheaths that surround the true stem. In almost all cases, they produce whip-like structures, either from the leaf apex (cirrus) or sterile inflorescences anchored to the leaf sheath (flagellum). Grapnels on the whips formed either from epidermal spines or from acanthophylls derived from reduced, reflexed leaflets help anchor the rattan to its support (see Putz, 1990 for further discussion on the mechanics of rattan climbing). The rattan habit can lead to immensely long stems; the longest unrooted stem ever recorded in any plant was recorded for a rattan, at about 172 m (Burkill, 1966). The true stem of a rattan is superficially bamboo-like, being cylindrical with well-defined scars, but, unlike bamboo, rattan stems are solid, conferring subtly different properties and applications for humans. These stems are more commonly known as rattan cane, which is the foundation of a multimillion-dollar industry in rattan products.

The majority of rattan species (463 species; POWO, 2024) occur in tropical Asia and the Pacific. The largest genus, *Calamus*, ranges from the Western Ghats in India, through mainland tropical Asia, the Indo-Malayan Archipelago and tropical Australia to Fiji (with one outlier species in tropical Africa). The highest diversity of rattan species is found on the Sunda Shelf (220 species; POWO, 2024), especially Borneo (131 species; POWO, 2024), with a secondary peak of species richness in New Guinea (64 species; Baker *et al*., 2024). The three remaining true rattan genera (*Eremospatha, Laccoserma* and *Oncocalamus*) are endemic to tropical Africa, which, although calamoid, are not directly related to the genera in the Asia-Pacific. *Desmoncus* is found in the tropical Americas, whereas the climbing *Chamaedorea* species occur in central America. The entire *Dypsis* genus is endemic to Madagascar.

Climbing palms are dependent on forests for their establishment and survival. Although some species can thrive in disturbed and secondary habitats, and some can even be grown in plantation settings, rich rattan floras thrive only in rainforests. Inevitably, the decline of rainforests worldwide has had a corresponding impact on climbing palm diversity and abundance. In addition, rattan is an extremely valuable non-timber forest product that continues to be extracted largely from the wild. Cane from rattan and other climbing palms is immensely valuable for weaving furniture, handicrafts and utensils, as well as in construction, among many other uses (Johnson and Sunderland, 2004). It is used extensively locally and is also exported in large quantities. The growing popularity of furniture and other items made from rattan in global markets serves to put greater pressure on wild rattan populations. Overall, more than 150 rattan species have documented uses (Johnson and Sunderland, 2004), although the true number is likely to be much higher. Currently, however, it is difficult to understand the status of climbing palms in the wild due to a lack of evidence. For example, only 45 species of climbing palm are documented on the IUCN Red List of Threatened Species (as of 2024), of which only 12 fall into a threatened category (Critically Endangered,

Endangered or Vulnerable). With fewer than 10 percent of species evaluated, it is unlikely that an accurate understanding of extinction risk in climbing palms has been achieved. Work is underway to assess species in key areas (e.g. Borneo, New Guinea, Sulawesi and Viet Nam) as an essential precursor to more in-depth field studies to better understand standing stocks of rattan and the most effective means by which they can be used and managed sustainably.

4.5 Threats to tree species

The main threat to tree species is habitat loss due to agricultural expansion, affecting 29 percent of assessed species, followed by logging and other forms of wood harvesting (27 percent), livestock farming (14 percent) and infrastructure development (13 percent) (BGCI, 2021). Other threats affecting large numbers of tree species include changes in fire regimes, energy production, mining, and the presence of invasive species. The impacts of climate change are likely to intensify in future, with trees in island, coastal, dryland and montane ecosystems the most vulnerable due to a combination of rarity/speciation, high exposure to changing climatic conditions, and an inability to migrate (Enquist *et al.*, 2019; Tejedor Garavito *et al.*, 2015). Climate change can also interact with other threats, such as fire and the spread of pests and diseases, often intensifying their impacts. Many threats interact with each other. Most of the threats discussed here were reported by countries for this report (see Chapter 10 for more discussion).

The relative importance of different threats to tree species varies (Rivers *et al.*, 2022). In temperate zones in Europe, North America and North Asia, the main threats to tree species are invasive species and pests and diseases; in tropical regions, the main threats are loss of habitat to agriculture (including livestock husbandry) and biological resource use (e.g. logging). Urban and industrial development is a major threat in many regions, and natural-system modification is a significant threat in Africa, Europe and the Southwest Pacific (Rivers *et al.*, 2022).

In the past, reforestation and afforestation have tended to use introduced fast-growing tree species and, to a much lesser extent, native species. Increasingly, the aim of tree-planting efforts is to restore natural forests through natural or assisted regeneration and the use of genetically diverse planting stock (e.g. Gaisberger *et al.*, 2023; Nelson *et al.*, 2024). Such efforts will play a crucial role in safeguarding the genetic diversity of trees and other woody plants.

4.6 Conclusions

The assessment of the world's tree species has advanced and the most recent account of the number of named tree species is about 57 700 in 266 families, the majority of which are in Africa, Asia and Latin America and the Caribbean. There are also an estimated 1 600 woody bamboo and more than 31 percent of rattans (>150) species and nearly 500 species of rattans. A quarter of tree species (about 14 000), 12 percent of bamboos (195) and more than 31 percent of rattans (>150) have documented, and often multiple, uses. About 30 percent of all tree species are considered threatened, while no comprehensive threat assessment has been carried out for bamboos and rattans. Islands are of particular conservation concern: of the top 15 countries and territories for percentage of threatened tree species, all except Chile are islands. Relatively few bamboo species are common and widespread, and most are rare. Moreover, their descriptions remain incomplete, and the generic classification of bamboos is in flux. Insufficient data are available to adequately understand the status of climbing palms (rattans) in the wild.

Chapter 5

Genetic diversity in trees and other woody plants

5.1 Introduction

This chapter presents the state of genetic characterization and a summary of the information reported by countries on the genetic diversity of tree and other woody plant species. It discusses how ecological and life-history traits and different drivers of demographic change shape genetic diversity, and it presents an overview of knowledge on genetic diversity in different forest biomes based on recent scientific literature focused on forest trees.

Genetic diversity and gene flow

Trees and other woody plants adapt to environmental change and evolve by means of their genetic diversity (FAO, 2014a). When novel challenges (e.g. pathogens or drought) arise, populations with higher genetic diversity are more likely to feature individuals with the necessary genes and associated functional traits to survive and adapt to the challenge. In a stable environment, high genetic diversity enhances the likelihood that natural selection will purge maladaptive traits (i.e. those with a negative impact on fitness) in favour of beneficial variants, thus helping a species improve its performance in adapting to local conditions. For both plants and animals, there is often a positive correlation between genetic diversity and population fitness, with one study finding that this correlation explained up to 19 percent of fitness variation (Reed and Frankham, 2003). In contrast, populations with low or declining genetic diversity have fewer opportunities to cope with and adapt to change and are therefore at a higher risk of extinction.

Genetic diversity is the variation in deoxyribonucleic acid (DNA) sequences within and among individuals, populations and species.[11] New genetic variation arises via mutation and sexual reproduction. A gene is a sequence of DNA that controls a particular trait or function; in forest trees, multiple genes, or gene families, typically control a given trait (Plomion *et al*., 2016a).

Traits are measurable attributes of an individual, and their effect on fitness may be beneficial, disadvantageous or neutral. A *functional* trait is known to influence the fitness and performance of an individual. In trees, functional traits may be morphological (e.g. height, diameter and leaf area), physiological (e.g. photosynthetic capacity), or biochemical (e.g. chlorophyll or lignin content) (Bian *et al.*, 2022).

In addition to mutation and selection, gene flow is a crucial driving force behind the composition and level of genetic diversity within a species. Gene flow refers broadly to any mechanism resulting in the movement of genetic variants from one population to another through the movement of gametes (i.e. reproductive cells such as seeds and pollen), individuals, and even populations (Slatkin, 1987). A tree population can be defined as a group of interbreeding individuals of a species in a geographical location that is genetically isolated (no gene flow) from other populations of the same species (FAO, 2014a).

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[11] See FAO (2014a) for a more detailed explanation of this and other basic concepts related to FGR.

In practice, however, it is difficult to delineate tree populations because forests and woodlands often span vast swathes of land and many trees have extensive gene-flow capabilities (Petit and Hampe, 2006).

In forest trees, natural gene flow occurs primarily through seed and pollen movement. Extensive gene flow is associated with high levels of genetic diversity and low levels of non-adaptive genetic structure. Genetic structure increases when gene flow is restricted (e.g. by features in a landscape, habitat fragmentation, or pollinator limitation). In some cases, genetic isolation can also lead to unique genetic divergence, resulting in local niche adaptations, genetic distinctiveness, and even speciation.

Forest trees typically have high genetic diversity within populations and large effective population sizes (see Petit and Hampe, 2006). Most forest tree species have maintained high genetic diversity and their evolutionary potential throughout the profound environmental changes that have taken place in the last 2.6 million years (the Quaternary period) (Milesi *et al*., 2024), a feature of the predominance of outcrossed reproduction and extensive gene flow. In more recent times, however, deforestation and forest degradation (see Chapter 2), as well as overharvesting and other drivers of change (see Chapter 10), have eroded the genetic diversity of many forest tree species. SoW-FGR1 documented many examples of valuable tree species that have lost genetic diversity due to these drivers (FAO, 2014a). Genetic diversity losses occur through reductions in the range of individual species (extinction of whole populations) and in the size of remnant populations (reduced diversity within populations). Although genetic diversity has been well studied in many forest trees, no global estimate is available of the loss of genetic diversity. Genetic erosion in agricultural crops is well documented in terms of losses of varieties and landraces, but the actual amount of lost genetic diversity remains unquantified (Khoury *et al*., 2022). Using the geographic range reductions of species as proxies, Exposito-Alonso *et al*. (2022) estimated that more than 10 percent of genetic diversity could have been lost globally across many animal and plant species. Genetic erosion is continuing worldwide, even in common and widespread species, and active management is necessary to halt the loss of genetic diversity (Shaw *et al*., 2025).

5.2 Characterization of genetic diversity

Genetic diversity can be quantified using expressed traits or molecular-level variation. The first approach is based on the assessment of quantitative variation of traits among tree populations grown under common environmental conditions in the field or in a greenhouse or nursery, and the second uses molecular laboratory tools. Expressed variation can also be assessed using morphological and physiological studies, but the results cannot be attributed to genetic differences unless the environmental effect is controlled.

Morphological evaluation can also be unreliable because many tree species can alter their phenotypes in response to environmental variables without detectable changes in their genetic makeup. Such phenotypic plasticity in trees is widely documented. For example, several subspecies of jarrah (*Eucalyptus marginata*) have been described based on phenotypic variation, but research has shown little genetic differentiation among its populations in southwestern Australia (Wheeler *et al*., 2003). This plasticity is also apparent at the individual level, as shown in *Betula pendula,* where a single tree reduced its number of stomata in response to rising carbon dioxide levels (Wanger *et al*., 1996).

SoW-FGR1 presented a historical account of provenance trials established for many valuable tree species in different regions from the early twentieth century (FAO, 2014a). It showed that countries recognize the crucial role of provenance trials in characterizing genetic variation within species and in identifying seed sources for reforestation and establishing planted forests outside species' native ranges. SoW-FGR1 also highlighted the importance of multilocation provenance trials and particularly reciprocal transplant trials in providing information on the adaptation of forest trees to different environments and hence also to climate change.

Reciprocal transplant trials compare the performance of a given set of populations or individuals by growing them within and outside their local or "home" environment. Fitness (e.g. height and survival) can be assessed for evidence of local adaptation (i.e. those provenances performing best in local conditions) and its scale. Reciprocal transplant trials can also detect suboptimal adaptation to the local environment (when a local provenance performs poorly compared with non-local provenances), which is increasingly important in the face of climate change. Reciprocal transplant trials are particularly useful for selecting well-adapted seed sources for a given site under projected climatic change.

Provenance trials are effective in determining whether the variation of functional traits has an underlying genetic basis, and their results are valuable for predicting the likely performance of a given provenance in practical forestry. The downside of these trials is that they are costly and time-consuming. Forest trees can take decades to reach reproductive maturity and provide reliable results (Gibson *et al.*, 2016; Kawecki and Ebert, 2004), although the time needed can be considerably less in tropical and subtropical regions than in temperate regions.

SoW-FGR1 presented an overview of laboratory-based techniques for assessing molecular-level genetic diversity in forest trees (FAO, 2014a). At the time of that report, DNA markers had largely replaced isozyme markers and led to a surge in DNA-based studies that relied on genome sequencing and advancing the identification of specific genes and their function, although SoW-FGR1 highlighted the need to link expanding gene-level information with whole-organism information from forests and field trials.

DNA-based approaches have become more affordable and accessible over the last two decades, and whole genome sequences have been published, or are under production, for a growing number of species (Li *et al.*, 2022; Holliday *et al.*, 2017). Advanced methods can sequence millions of small DNA fragments simultaneously, thus drastically reducing the time needed to sequence entire genomes or parts of many genomes. Genomic studies have also been used increasingly to support FGR conservation (Isabel *et al.*, 2020), such as in identifying populations with genes that are resistant to pests, assessing the adaptive potential of species in the face of climate change, designing frameworks for genetic rescue and assisted migration, and analysing populations for their genetic diversity (Borrell *et al.*, 2020; Ingvarsson and Bernhardsson, 2020; Isabel *et al.*, 2020; Parent *et al.*, 2020; Isabel *et al.*, 2020).

The development of reference genomes has become more common. These references are "ideal" genomes that represent the whole genome sequence of a species with crucial information, such as the location of specific genes. Reference genomes are constructed from a range of individuals, and they provide researchers with a framework for assembling genetic data for identifying specific genes under selection.

The first fully annotated tree genome was black cottonwood (*Populus trichocarpa*) (Tuskan *et al.*, 2006), and many reference genomes of tree species are now available in public databases (e.g. 38 genomes in TreeGenes). A significant challenge in sequencing the whole genomes of forest trees, however, is their variation in size and repetitive regions. For example, gymnosperm genomes can be enormous (the genome of Scots pine – *Pinus sylvestris* – is more than 22 gigabase pairs – gbp) (Pyhäjärvi, Kujala and Savolainen, 2020). Gymnosperm genomes can also have high frequencies of repetitive regions. Wegrzyn *et al.* (2014) estimated that such regions account for up to 82 percent of the 22 gbp loblolly pine (*Pinus taeda*) genome. Angiosperms tend to have smaller genomes, likely due to genome downsizing in their evolutionary past (e.g.

pedunculate oak, *Quercus robur*, has a genome size of 1.5 gbp) (Simon and Roddy, 2018; Plomion *et al.*, 2016a). Sequencing larger genomes is more resource-intensive and therefore more expensive (due to both the cost of sequencing and the skills required to analyse the data), and questions arise over the cost/value ratio when sequencing many repetitive regions.

Coinciding with the increase in genomic data for tree species is the need to integrate the data into accessible databases. The TreeGenes database, for example, collates genomic, protein and ribonucleic acid (RNA) data (and the literature) for nearly 2 500 tree species and provides access to tools and pipelines for interacting with and managing the data (Wegrzyn *et al.*, 2020; Falk *et al.*, 2018). Users can contribute to this database, but it also sources data from repositories such as GenBank. Genome databases help standardize the format of genomic data and increase accessibility. Developers are now adding tools and workflows to assist in analysing data (Wegrzyn *et al.*, 2020; Falk *et al.*, 2018). One such tool is the online CartograTree, which can analyse TreeGenes data in the context of geographical location for phylogenetic or population genetic studies (Wegrzyn *et al.*, 2019; Vasquez-Gross *et al.*, 2013).

5.3 The state of knowledge on tree genetic diversity reported by countries

Of more than 2 800 species (including hybrids) reported by countries for this report, 1 661 have been characterized based on non-molecular information (typically provenance trials) and 750 have been characterized based on molecular information (e.g. range-wide sampling of populations for molecular marker studies). Table 8 shows the regional breakdown of the characterized species. Relatively few species in Africa and the Near East have been characterized based on molecular information compared with non-molecular characterization, albeit this finding is based on a low number of reporting countries in these regions.

TABLE 8
Number of reported species, by region, that have been characterized for genetic diversity based on non-molecular and molecular information

Region	**Number of species***	
	Non-molecular information	Molecular information
Africa	529	35
Asia	388	367
Europe	200	136
Latin America and the Caribbean	612	159
Near East	32	10
North America	85	91
Southwest Pacific	42	45

Notes: * Net number of species reported by region. Based on date provided by country reports.

Several countries reported that provenance trials – many of them established decades ago – continue to provide crucial information on genetic diversity in forest trees. Many countries pointed out that provenance trials have also proved invaluable for evaluating the effects of climate change on tree populations and for developing strategies for countering its negative impacts. The usefulness of early provenance trials may be limited, however, due to difficulties in accessing old data as well as weaknesses in statistical design. Although costly, some countries have reported establishing new provenance trials in the past decade or are planning to do so. The United Kingdom of Great Britain and Northern Ireland, for example, reported a scoping study to identify vulnerabilities in existing provenance trials and to halt the deterioration of research infrastructure. The United Kingdom further noted that better characterization of native tree and shrub species is required to inform conservation efforts, forest management, seed production and tree-improvement strategies.

The country reports showed that the most frequently used markers for molecular characterization are microsatellites (simple sequence repeats – SSRs) and single-nucleotide polymorphism (SNP) markers, as they were in SoW-FGR1 (FAO, 2014a). Genomic approaches have continued to increase knowledge on the genetic basis of adaptation in trees, and these studies have typically focused on selected species. Canada, for example, reported that white spruce (*Picea glauca*) has emerged as a model species because it is by far the country's most studied conifer species. Canadian research teams have produced results on organelle sequencing, gene structure, variation in gene copy number, development of SNP genotyping arrays, association analysis, and gene expression. In addition to improving knowledge on the genetic basis of adaptation, this has advanced understanding of evolution, defence mechanisms and the genes involved in wood formation.

Australia also reported genomic advances, with the availability of 26 eucalypt genomes (deposited in the GenBank database) following publication of the first reference genome of flooded gum (*Eucalyptus grandis*) in 2014 (Myburg *et al*., 2014). Australia reported the completion of anchored genomes for macadamia (*Macadamia integrifolia*) (Nock *et al*., 2020) and lemon-scented gum (*Corymbia citriodora*) (Healey *et al*., 2021).

The country reports do not allow a detailed assessment of progress in characterizing the genetic diversity of trees and other woody species. Many countries noted that information on both non-molecular and molecular characterization is not gathered and stored systematically at the national (or subnational) level. Few countries have databases on their provenance trials, although several reported carrying out surveys to map relevant studies published in the past decade while preparing their reports for the present assessment.

The first global assessment did not report the number of species for which genetic diversity has been characterized but noted that genetic-level information was available for 300–400 species and that 241 species were included in biotechnology research (FAO, 2014a). The findings of the present report suggest that the characterization of genetic diversity with molecular tools has expanded to many new species in the last decade, with several countries (e.g. Argentina, Australia, Brazil, Canada and Germany) reporting an increasing number of studies based on molecular techniques. In Brazil, for example, more than 220 scientific papers using molecular techniques were published between 2011 and 2021 with information on the genetic diversity of 55 native tree species and 34 introduced tree species. Canada also reported the publication of at least 43 studies since 2012 that assessed genetic diversity for part or all the distribution of 27 native tree species.

Although the number of species characterized for their genetic diversity has increased, fewer than 3 percent of the world's tree species have been characterized using non-molecular methods and just over 1 percent have been characterized using molecular techniques. Overall, the country reports show that the characterization of genetic diversity has focused on economically important and threatened species in the genera *Abies*, *Acacia*, *Albizia*, *Betula*, *Eucalyptus*, *Fraxinus*, *Handroanthus, Larix*, *Myrceugenia*, *Nothofagus*, *Picea*, *Pinus*, *Populus*, *Quercus* and *Terminalia* (Table 9).

Evolutionary processes and human impacts continuously shape the genetic diversity of trees and other woody plants over time and large geographical areas. Identifying a long-term trend in the genetic diversity of a species would thus require assessing temporal changes in genetic parameters of different populations of the species using molecular methods.[12] The country reports show that the genetic diversity of tree and other woody plant species is not monitored systematically over time and that operational genetic monitoring systems are still in their

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[12] See Fussi *et al.* (2016) for an overview of genetic monitoring approaches.

TABLE 9
Top five genera characterized, by region, based on non-molecular and molecular information

Region	Top genera characterized (number of species reported)	
	Non-molecular information	Molecular information
Africa	*Eucalyptus* (15), *Pinus* (14), *Albizia* (12), *Terminalia* (11), *Combretum* (9)	*Pinus* (4), *Dypsis* (3), *Adansonia* (3), *Eucalyptus* (3), *Dalbergia* (2)
Asia	*Pinus* (22), *Quercus* (12), *Picea* (9), *Prunus (9),* *Abies* (8), *Populus* (8)	*Pinus* (23), *Populus* (11), *Abies* (11), *Magnolia* (7), *Quercus* (7), *Camellia* (7)
Europe	*Pinus* (22), *Quercus* (15), *Abies* (14), *Populus* (11), *Larix* (11)	*Pinus* (15), *Quercus* (15), *Abies* (10), *Larix* (9), *Populus* (9)
Latin America and the Caribbean	*Eucalyptus* (33), *Pinus* (31), *Myrceugenia* (15), *Handroanthus* (13) *Nothofagus* (11)	*Pinus* (22), *Eucalyptus* (18), *Nothofagus* (7), *Cedrela* (6), *Neltuma* (5)
Near East	*Quercus* (5), *Prunus* (3), *Acer* (3), *Juniperus* (3), *Arbutus* (2), *Pinus* (2)	*Quercus* (4), *Prunus* (2), *Pinus* (1), *Cedrus* (1), *Ceratonia* (1), *Cupressus* (1)
North America	*Pinus* (19), *Picea* (7), *Abies* (6), *Acer* (6), *Populus* (5), *Fraxinus* (5), *Larix* (5)	*Pinus* (14), *Picea* (7), *Fraxinus* (7), *Abies* (6), *Populus* (5), *Betula* (5), *Quercus* (5), *Acer* (5), *Larix* (5)
Southwest Pacific	*Eucalyptus* (21), *Acacia* (6), *Pinus* (5), *Corymbia* (3), *Macadamia* (2)	*Eucalyptus* (14), *Acacia* (7), *Pinus* (4), *Corymbia* (4), *Macadamia* (2), *Araucaria* (2), *Elaeocarpus* (2)

Notes: Based on date provided by country reports.

infancy. This means a considerable shortfall in the implementation of both the CBD, which calls for the monitoring of all components of biodiversity in its Article 7, and the Global Plan of Action, which urges countries to establish and strengthen national FGR assessment, characterization and monitoring systems (FAO, 2014b). The lack of assessment of temporal changes in genetic diversity is not limited to trees and other woody plants – it is a problem for all species. Of more than 80 000 studies screened for a global meta-analysis across terrestrial and marine realms, only 1 percent measured temporal changes in genetic diversity (Shaw *et al*., 2025).

SoW-FGR1 found that most countries recognize the utility of genetic monitoring but that only Germany had initiated such a monitoring system (FAO, 2014a), which it had done by creating the first permanent monitoring plots for European beech (*Fagus sylvatica*) and wild cherry (*Prunus avium*) (with four and five plots, respectively) (Konnert *et al*., 2011). For the present assessment, Germany reported expanding the genetic monitoring system to 24 plots for European beech and Norway spruce (*Picea abies*) between 2016 and 2020. Several other European countries have also made progress in this regard. Greece and Slovenia reported the establishment of genetic monitoring systems (both countries with two plots). Lithuania has carried out pilot studies of monitoring genetic diversity in gene reserves, seed stands and managed forests. Sweden reported discussions among authorities and researchers on creating a monitoring system for genetic diversity in several organism groups, including forest trees. All these countries noted benefiting from the work of the EUFORGEN network in promoting a pan-European approach to the genetic monitoring of forest trees (Aravanopoulos *et al*., 2015).

For the present report, countries were invited to provide information on possible temporal trends in the genetic diversity of trees and other woody plants. In reporting on such trends in the absence of comprehensive genetic monitoring systems, countries mostly relied on expert opinion and earlier published studies on the amount and distribution of genetic diversity in tree populations. Most such studies assessed genetic diversity at only one point of time, and once-sampled tree populations have seldom been subjected to follow-up genetic studies. Moreover, no country reported systematically collecting and storing population-level samples that would allow retrospective analyses over time, although one opportunity that could be explored in the future is the use of seedbank material. Some countries also based their reporting on trends in changes in the distribution ranges and population sizes of species.

At the global level, information provided by countries indicates that the genetic diversity of trees and other woody plants continues to decline due to deforestation, forest degradation, fire, pests and diseases, and invasive species. Several countries also indicated that they expected climate change to accelerate local population extinctions in many species, further eroding genetic diversity. The extent of genetic diversity loss remains largely unquantified, however, because of the lack of temporal genetic data in most reporting countries.

The country reports indicated that genetic diversity is not being lost evenly across forest biomes (see section 5.5 for discussion on biomes) and that genetic erosion is higher in tropical and subtropical forests than in boreal and temperate forests. In tropical and subtropical forests, many tree and other woody plant species tend to occur scattered across landscapes. The occurrence of endemic and threatened species is also highly concentrated in the tropical and subtropical regions (see Chapter 4). In boreal and temperate forests, widely distributed and stand-forming species with large population sizes are typically predominant, and their ecological and life-history traits favour the maintenance of genetic diversity. Many countries in Europe and North America, which generally have compiled more genetic data than countries elsewhere, indicated that the state of genetic diversity is considered stable at a high level, with the exception of rare and endangered species.

The report for Australia mentioned that few studies on the country's trees and woody shrub species have analysed genetic diversity over time, but it offered an interesting example. Coates *et al*. (2015) quantified the effects of local population extinction on the genetic diversity of an endemic and threatened woody shrub species, *Banksia brownii*, by comparing extinct and extant populations of the species (*ex situ* seed collections were used as samples for now-extinct populations). The study found that nearly 40 percent of the total genetic diversity of the species was lost following population extinctions over a 25-year period driven by the introduced pathogen *Phytophthora cinnamomi* (Coates *et al*., 2015).

There is evidence that reductions in the number of populations and the overall abundance of species do not always cause significant losses in genetic diversity. The United States of America, for example, reported that the geographical range of longleaf (*Pinus palustris*) and shortleaf (*P. echinata*) pines contracted considerably in previous decades but that appreciable genetic diversity of the species remains (Schmidtling and Hipkins, 1998; Stewart *et al*., 2016). Another example mentioned by the United States of America is American chestnut (*Castanea dentata*), which was decimated by chestnut blight introduced from Asia in the late nineteenth century. Despite a large reduction in the species' range and census number, genetic diversity remains reasonably high (Gailing and Nelson, 2017; Sandercock *et al*., 2022). Nevertheless, the species remains at a high risk of extinction because it mainly survives as an understorey shrub that reproduces vegetatively by root sprouts and because few blight-resistant mature trees remain, thus limiting the sexual reproduction needed to increase genetic diversity.

Given that genetic diversity is assessed with molecular techniques for only a tiny proportion of the world's tree and other woody plant species, alternative means are needed for evaluating the genetic diversity of such species with a view to improving their genetic management. Ultimately, it is infeasible in practice to monitor the genetic diversity of all woody species using molecular techniques. Ecological and life-history traits provide useful information on how well a given species is expected to maintain its genetic diversity in the face of threats and disturbances.

5.4 Within-species attributes shaping genetic diversity

Evolutionary history and reproductive and ecological traits define the levels and structure of genetic diversity within species. These traits interact with environmental forces, further shaping genetic diversity. Consequently, life-history traits and both historical (e.g. glacial cycles) and contemporary (e.g. recent habitat clearance) biogeography are crucial considerations for FGR management (Table 10).

Ecological and life-history traits

Ecological traits refer to the interactions of a species with its environment (e.g. preferred habitat) and life-history traits relate to a species' life cycle (e.g. when it reaches sexual maturity). Meta-analyses of plants have shown associations between genetic diversity and these traits (Hamrick and Godt, 1996). For example, range size, growth form and mating system can be significant predictors of genetic diversity, and growth form, seed dispersal vector and mating system are associated with species-wide genetic structure (Lowe *et al.*, 2018; Broadhurst *et al.*, 2017; Ellegren and Galtier, 2016; Hamrick and Godt, 1996).

Plant species with larger growth forms, such as trees, tend to live longer and have more overlapping generations over time, which generally means that trees have reasonably high genetic diversity and thus some cushioning against the loss of genetic diversity (Petit and Hampe, 2006). The fact that trees grow slowly protects genetic diversity and allows individuals to mate across overlapping generations, ensuring the maintenance of rare alleles in gene pools. Older trees harbour genetic diversity that might otherwise be lost (e.g. from genetic drift due to habitat fragmentation), providing a genetic buffering that supports the maintenance of genetic diversity through generations (Hamrick, 1978). The presence of older generations could also slow down local adaption in a population, however. In theory, this lag effect could manifest in the harbouring of alleles no longer fit for site conditions because the older trees established under different climatic conditions – but this effect needs further study.

Plant species can be grouped into categories based on their geographic ranges, as follows (Hamrick, Godt and Sherman-Broyles, 1992):

- *endemic/localized* – known from only one or a few populations in one locality;
- *narrow* – found over several to many populations in a relatively restricted area, such as parts of one or a few countries or political units;
- *regional* – found throughout a geographic region or a significant portion of a continent; and
- *widespread* – found throughout a continent or on more than one continental mass.

Many forest tree species are widespread and grow in diverse environmental conditions. They are likely to display high genetic variation across their range and have the capacity to adapt and respond to changing environments. In general, widespread species tend to have higher levels of genetic diversity than those ones with narrow ranges. For example, an early study of 332 woody taxa identified significant relationships between woody plants and their life histories and ecological traits (Hamrick, Godt and Sherman-Broyles, 1992). On average, endemic and highly localized species had approximately 70 percent less genetic diversity than widespread species and more than 50 percent less genetic diversity in the regional/narrow category; widespread species, in contrast, had 34 percent higher genetic diversity than those with regional or narrow ranges (Hamrick, Godt and Sherman-Broyles, 1992). Recent research supports these early findings. For example, Wollemi pine (*Wollemia nobilis*) has only one known population in a remote canyon in New South Wales, Australia. The wild population consists of an estimated 89 (46 mature) individuals and has extremely low (yet detectable) genetic diversity and variation (Mackenzie *et al.*, 2022). Conversely, Scots pine (*Pinus sylvestris*) is one of the most widespread tree species on Earth, spanning Asia and Europe. Including plantations, Scots pine is estimated to cover 145 million ha. It has relatively high genetic diversity compared with less widely distributed taxa and generally low levels of genetic differentiation between populations (Pyhäjärvi *et al.*, 2020; Durrant *et al.*, 2016).

Plants have complex mating systems that vary between and even within species. These systems can also influence and interact with their environment (e.g. fragmentation that limits mate choice). Mating systems range from complete outcrossing (sexual reproduction with a different individual, often achieved by having male and female flowers on separate individuals), through various self-incompatibility mechanisms that encourage outcrossing in hermaphrodite species, to autogamy (self-pollinating). There is also a range of intermediate systems (known as mixed mating) (Imai *et al.*, 2016; Schoen *et al.*, 1996). Many forest trees (e.g. *Populus* spp.) can also reproduce clonally, which provides alternative reproductive assurance when other options are depauperate (Jeník, 1994). Because mutations in DNA (and, as such, new genetic variation) are typically formed and distributed through outcrossing sexual reproduction, genetic diversity tends to be higher in outcrossing species. On the other hand, mating-system selection is a compromise. Although clonality and autogamy remove the need to find suitable mates and thus provide greater reproductive assurance, they come at the cost of the extra diversity that sexual reproduction and outcrossing introduce.

Outcrossing, therefore, is a crucial process for introducing and maintaining genetic diversity. The availability of potential mates limits this system, as does the presence and type of pollinators (depending on the species' pollination method). To counteract such limitations, many plant species, including many tree species, can switch between mating systems depending on mate availability and the relatedness of mates (Eckert *et al.*, 2010). Nevertheless, in forest tree species, outcrossing tends to prevail. For example, a study of 45 neotropical forest tree species found that 90 percent of them were preferential outcrossers (Lowe *et al.*, 2018). Outcrossing tree species have been observed to suffer from inbreeding depression when they switch to self-fertilization. For example, there might be a reduction in seed-set of up to 90 percent in self-pollinating Douglas fir (*Pseudotsuga menziesii*) compared with outcrossing (Sorensen *et al.*, 1974). Self-pollinating Scots pine individuals were observed to set four times fewer seeds than outcrossing individuals (Koelewijn *et al.*, 1999). Conifers do not possess self-incompatibility systems, and inbreeding depression can manifest in various forms (e.g. reduced seedling survival and reduced height) across life stages; it is the main control mechanism for removing inbred material from future generations.

How a species disperses its pollen and seeds can determine the fundamental level of gene flow across its range (discounting factors that can disrupt or interact with this, discussed below). The greater the distance that pollen or seeds can travel, the greater the potential for gene flow. Although pollen usually has the potential to cross greater distances than seeds, the final destination of the next generation depends on where the seeds can disperse to and establish. Most gymnosperms, including all conifers, are wind-pollinated. Up to 86 percent of angiosperms (flowering plants, including many trees) are animal-pollinated (Hu *et al.*, 2008), although a large proportion of angiosperms originating in temperate and boreal regions are wind-pollinated (e.g. many *Quercus* species). Animal and wind pollination are two major life-history categories that shape genetic diversity. Wind-pollinated tree species tend to have far-reaching pollen dispersal but rely on what is a somewhat random dispersal technique (Kling and Ackerly, 2021).

Animal pollinators provide cross-pollination, but the extent of dispersal is limited by their availability, movements and behaviours. In a review of pollen dispersal in tree species in the neotropics, Dick *et al*. (2008) showed that both the size and behaviour of pollinators affect dispersal distances: smaller insects (with exceptions) have shorter pollen dispersal ranges (often less than 300 m); larger insects (e.g. bees) have the capability to disperse pollen more than 750 m; and bats can disperse pollen up to 18 km. Counterintuitively, Dick *et al*. (2008) showed that some of the smallest pollinators (*Ficus* wasps) were able to transport pollen 5–14.2 km by using air pockets above the forest canopy to disperse, highlighting nuances to any rules of thumb based on pollinator size alone.

The relationship between seed dispersal and gene flow follows a similar pattern: the greater the potential distance a seed can disperse, the greater the propensity for gene flow across a landscape. There are two broad types of seed dispersal: allochory, in which seeds use a transport vector, such as being attached to, or eaten by, animals; and autochory, in which seeds use gravity or explosive mechanisms. Hamrick, Godt and Sherman-Broyles (1992) studied 322 species to assess the impact of seed dispersal on the genetic diversity of woody species, using the following categories: gravity; gravity *and* animal-attached; explosive; wind; animal-ingested; and animal-attached. They found that animal-ingested seeds were associated with the highest levels of genetic diversity (and likely gene flow), and that wind and gravity were linked to significantly lower genetic diversity. For many tree species, secondary dispersal (e.g. via animal, air convection or water) can increase the distance of dispersal and may be important for long-distance dispersal and founder effects.

5.5 Drivers of change

Despite the relative resilience of forests to genetic diversity loss, deforestation, habitat fragmentation and certain logging practices can have an impact. Selective logging practices that remove too many mature trees can eliminate the genetic buffering of overlapping generations (Vranckx *et al.*, 2012; Aguilar *et al.*, 2006; Lowe *et al.*, 2005). Habitat fragmentation reduces the size of populations, meaning that fewer individuals are available to contribute genetic diversity to gene pools. Fragmentation can also disrupt gene flow between populations, thus limiting mate choice and increasing the likelihood that individuals will mate with relatives (or, in some tree species, become more likely to self-pollinate or reproduce clonally). Because relatives are more likely to share genes, this can lead to the appearance of maladaptive traits in populations due to inbreeding depression. Given variation in life-history traits, some species (e.g. those with limited or animal-dependent dispersal mechanisms) are more vulnerable to fragmentation, logging and clearance than others.

Evidence suggests that habitat fragmentation can reduce pollinator densities and alter their behaviour, potentially reducing opportunities for plant species to outcross. A study of the impact of habitat fragmentation on the genetic diversity of three eucalypt tree species found that the predominantly bird-pollinated species demonstrated lower levels of inbreeding than the two insect-pollinated species (Breed *et al.*, 2015). The same meta-analysis showed that habitat fragmentation increased the likelihood of these trees self-pollinating, but species with more-mobile pollinators were less likely to experience this transition (Breed *et al.*, 2015). Because birds have far greater mobility than invertebrates, bird-pollinated tree species may be less vulnerable to the negative impacts of habitat fragmentation.

It is important to distinguish the potential impacts for tree species that have specific pollinators from those that have more generalist pollinators (meaning they can be pollinated by a wider range of species). In the latter case, disruption to or the absence of a pollinator might be compensated by the presence of another. The post-fragmentation land-use matrix is also an important factor: for example, Lander *et al*. (2013) showed the importance of behavioural ecology (resource-based models) for interpreting pollinator behaviour in heterogeneous landscapes.

Understanding historical population dynamics can guide contemporary forest management by identifying populations with high genetic diversity that could be the focus of conservation efforts. During past ice ages, for example, forest trees became restricted to habitats not covered in ice, contracting and expanding their range based on available habitat. Range contraction essentially concentrates the genetic diversity of a surviving population or species in locations where it takes refuge until able to colonize newly available habitat (e.g. when ice retreats as it thaws). In periods of rapid expansion, not all genetic diversity will disperse at the same rate, and genetic refugia can still be detected using molecular methods and data analysis (e.g. Petit *et al.*, 2003). Some such refugia have been shown to harbour higher levels of genetic diversity than elsewhere in the species' range. This is the case for Scots pine, which has lower genetic diversity outside its refugia in northern Europe (Cheddadi *et al.*, 2006). Other pockets of high genetic diversity can also be found when multiple isolated refugia expand and meet, resulting in genetic admixture. In an analysis of more than 20 European tree and shrub species affected by glaciation, Petit *et al.* (2003) found that the most genetically diverse populations were more likely to be found in post-expansion meeting points of glacial refugia.

Characteristics of glacial refugia are known to influence structure in contemporaneous populations. For example, North American tree species with more extensive and widespread glacial refugia exhibit more differentiation between populations and subspecies, as well as higher genetic diversity (Roberts and Hamann, 2015). Glacial refugia have shaped the present-day genetic structure of tree populations in Argentina (Azpilicueta, Marchelli and Gallo, 2009). Other factors, such as topographic gene-flow barriers, also influence the demographic history of species and, in some cases, can be more important than glacial cycles for establishing distinct genetic clusters (Milesi *et al.*, 2024).

Understanding past population dynamics can provide a baseline for today's forest management by answering questions such as, "What is the minimum viable population size for maintaining genetic diversity?" and "Where is a species no longer found and why?". A recent study of several European tree species showed that effective population size was maintained (or even increased) during glacial cycles, suggesting that tree species can maintain large effective population sizes during profound environmental changes, which affords them certain resilience to such changes (Milesi *et al.*, 2024).

The historical effect of landscape on genetic composition is essential for considering the delimitation of conservation units (Moritz, 1994), and analysis of historical demography can help define conservation units for a species. For example, if multiple populations of a species retract to differing habitats (as happened during the Last Glacial Period) and become isolated from each other for long enough, they may begin separating evolutionarily due to a lack of connecting gene flow. Separation can lead to local adaptations, subspecies and speciation. Milesi *et al.* (2024) noted that increased elevation was associated with increased divergence, suggesting distinct subpopulations adapted to elevated, cold environments, in line with previous findings (Hirao *et al.*, 2017). Understanding such evolutionary histories provides insights that might be useful for forest management, such as in the design of environment-guided seed-transfer zones.

Multiple factors – such as precipitation, temperature and pests and diseases – affect the genetic diversity of tree species. Further research is needed to better understand how information on genetic diversity and gene flow can be incorporated into the adaptive management of forest trees (Holliday *et al.*, 2017).

Tree-breeding programmes can select seed sources based on their adaptative tolerances to future climate-change scenarios (e.g. increased drought) and other stressors such as pests and diseases. Ingvarsson and Bernhardsson (2019)

TABLE 10

Summary of predictions/core hypotheses of general patterns of levels of genetic diversity in plants, including but not limited to forest tree species, with respect to various drivers

Driver	Process	Genetic diversity	Category
Ecological and life-history traits	Range size	🟩	Widespread
		▨	Regional
		🟧	Endemic/localized
	Mating system	🟩	Outcrossing
		▨	Mixed
		🟧	Self-fertilization/clonality
	Gene flow – pollination/seed dispersal	🟩	Long distance (birds/wind)
		▨	Intermediate distance (invertebrates, vertebrates)
		🟧	Restricted (gravity seed dispersal)
	Gene flow – longevity/form	🟩	Long lifespan (>100 years)
		▨	Intermediate lifespan (20–100 years)
		🟧	Short lifespan (5–20 years)
Recent landscape context	Gene flow – habitat fragmentation	🟩	Continuous populations
		▨	Semi-continuous populations
		🟧	Fragmented populations
Demographic and evolutionary history	Gene flow – Demographic history (e.g. range disjunction)	🟩	Semi-continuous/continuous populations
		🟧	Highly disjunct (significant geographic barriers present, such as a mountain or large river)
Selective pressures from the environment	Environmental isolation (e.g. altitude, climate) or ecological pressures (e.g. pests, diseases)	🟩	Homogeneous environment (slight variation across its geographical range)
		🟧	Heterogeneous environment (e.g. spanning the elevation of a mountain, with significant climatic or soil differences)

Note: Dark green indicates expected/predicted high levels of genetic diversity, light green indicates intermediate levels, and orange indicates expected low levels.

Source: Adapted by the authors from **Hamrick, J.L., Godt, M.J.W. & Sherman-Broyles, S.L.** 1992. Factors influencing levels of genetic diversity in woody plant species. In *Population Genetics of Forest Trees: Proceedings of the International Symposium on Population Genetics of Forest Trees Corvallis, Oregon, USA, July 31–August 2, 1990* (pp. 95-124). Springer Netherlands. In Population genetics of forest trees, 95–124. Dordrecht, Springer. doi: 10.1007/bf00120641; **Broadhurst, L., Breed, M., Lowe, A., Bragg, J., Catullo, R., Coates, D. *et al*.** 2017. Genetic diversity and structure of the Australian flora. *Diversity and Distributions*, 23(1): 41–52. doi: 10.1111/ddi.12505; **Lowe, A. J., Breed, M. F., Caron, H., Colpaert, N., Dick, C., Finegan, B. *et al*.** 2018. Standardized genetic diversity-life history correlates for improved genetic resource management of Neotropical trees. *Diversity and Distributions*, 24(6): 730–741. doi: 10.1111/ddi.12716

combined whole-genome sequencing of 94 European aspen (*Populus tremula*) individuals with phenotypic trait and vegetative fitness analysis across a latitudinal gradient in Sweden. They found that northern populations were at risk of maladaptation due to predicted climate change in a relatively short period (less than 50 years), thus alerting practitioners to the need for more genetic management of these populations (such as facilitating gene flow from populations further south by planting material from those populations in northern areas). In North America, researchers identified up to nine genes in white spruce (*Picea glauca*) that correlate with chemical mechanisms that defend the species against defoliation by spruce budworm without compromising desirable growth traits, making trees with these genes promising candidates for future breeding programmes (Parent *et al.*, 2019).

5.6 Patterns of genetic diversity in forest biomes

Forest biomes

Terrestrial biomes can be defined in many ways, but macroclimate is considered the most important factor in determining the dominant vegetation (Mucina, 2019). For FRAs (see Chapter 2), FAO defines the main forest biomes as tropical, subtropical, temperate and boreal (FAO, 2012). David *et al*. (2020) presented a global typology of all Earth's ecosystems, which included, in the terrestrial realm, tropical–subtropical forests, temperate–boreal forests and woodlands, and shrublands and shrubby woodlands. The first two of these coincide broadly with the biomes used in the FRA. Biomes are useful concepts (see Mucina, 2019, for detailed discussion) for considering the overall pattern of genetic diversity of tree and other woody plant species, for at least two reasons. First, biomes are dynamic communities that change spatially and temporally, and this change drives the evolution and adaption of species therein. Analysing the genetic structure of the constituent species of biomes enables a better understanding of their evolutionary history (e.g. Hu *et al.*, 2020). Second, the influence of a biome on the genetic diversity and genetic distribution of species can be assessed and compared with other regions to ascertain what is typical – because each biome has a variety of species with differing life histories and ecological traits (Broadhurst *et al.*, 2017). This information has long been used in practice to guide conservation efforts (e.g. Newton *et al.*, 1999), and recent studies have continued to provide insights into how genetic diversity is distributed within a species' range in a given biome (e.g. Lyam *et al.*, 2022). Chapter 6 presents other recent studies on range-wide mapping of genetic diversity and the use of their results in FGR conservation. Below, general patterns of genetic diversity are summarized for the three major forest biomes, as defined by David *et al*. (2020), based on selected recent studies. The common feature of these biomes is the prevalence of trees and other woody vegetation.

Tropical–subtropical forests

Tropical forests stretch across the equatorial regions of Africa, Latin America and the Caribbean, and Southeast Asia, transitioning into subtropical forests at 23.5° North and 23.5° South of the equator. Tropical rainforests occur in lowlands, where temperature and precipitation are high and relatively constant year-round, and they are densely populated by evergreen broadleaf trees (Pearcy and Robichaux, 1985) (deciduous trees are also sometimes present). Subtropical rainforests, which occur (for example) in southern China and southern Brazil (Chi *et al.*, 2017; Keith *et al.*, 2022), exhibit similar characteristics to tropical rainforests but have a semi-evergreen character, with a higher proportion of deciduous or partly deciduous tree species due to seasonal precipitation.

Tropical and subtropical dry forests receive less precipitation than rainforests and experience long (up to eight-month) dry seasons. They occur inland and in some coastal areas of southern Asia and in Latin America. Trees are smaller in stature and have a higher proportion of deciduous species than tropical and subtropical rainforests (Murphy and Lugo, 1986).

Tropical and subtropical montane forests occur throughout the tropics in mountain uplands and foothills. Temperatures are lower in these forests than in humid and dry tropical forests, and precipitation is relatively constant due to cloud cover at high altitudes (Bruijnzeel and Veneklaas, 1998). Altitude also drives speciation and dictates simpler forest structures and species compositions (Salinas *et al.*, 2021).

Genetic differentiation within species tends to be high in lowland tropical forests, for several reasons. Species often occur in low population densities and have smaller ranges, and pollination is mainly animal-mediated (Loveless, 1992; Thang *et al.*, 2020). Gravity is the primary seed dispersal mechanism because wind speeds tend to be relatively low due to the high vegetation density (Degen and Sebbenn, 2021). Highly asynchronous precipitation patterns over short distances may also be a driving factor because this can dictate flowering patterns and pose a potential barrier to gene flow (Gamba and Muchhala, 2020). It has been noted that pioneer species have higher genetic differentiation and lower genetic diversity than later successional-stage trees due to founder effects (where populations have lower genetic diversity because they are descended from a small number of colonizers) (Lowe *et al.*, 2018).

Similar levels of genetic diversity have been observed for trees in temperate and tropical biomes (Loveless, 1992). Tropical trees use various methods to maintain genetic diversity. Outcrossing is widespread and highly preferential among species, although rates vary across taxa (Ward *et al.*, 2005). Many tropical tree species have self-incompatibility mechanisms, such as growing only male or female flowers on individual trees and selecting for outbreeding through forced mating with genetically distinct individuals (Degen and Sebbenn, 2021). There is also evidence that the pollen-dispersal mechanisms of tropical trees have greater ranges than might be expected, with many capable of carrying pollen hundreds or thousands of metres, which helps maintain gene flow and supports outcrossing for populations (Ward *et al.*, 2005). As a result of this, tropical and subtropical tree species often present with genetically differentiated subpopulations that are themselves genetically diverse (Lowe *et al.*, 2018).

The genetic resilience of tropical tree species is especially vulnerable to deforestation and forest fragmentation, which alter gene flow and the often-delicate relationships relied on for pollination, thus depriving tropical tree species of the means for maintaining high genetic variability (Vinson *et al.*, 2018). Studies have also shown that outcrossing is reduced in some logged and fragmented tree populations, which may result in reduced fitness and genetic diversity (Ward *et al.*, 2005) unless removed from the regenerating cohort by selection.

Temperate and boreal forests and woodlands

Temperate and boreal forests and woodlands are widely distributed in the Northern Hemisphere, covering large areas of Asia, Europe and North America. Smaller temperate forests and woodlands exist in Australia, New Zealand and South America (Willis, 2009). Deciduous broadleaf trees are prevalent in temperate forests (except in Australia), and conifers dominate boreal forests (Apps *et al.*, 1993).

Marked seasonality is a significant feature of temperate forests, driven by large temperature changes between winter and summer. This variability regulates tree growth and breeding and divides annual life cycles into two phases. Summer months are characterized by active tree growth. Trees enter hibernation in winter, facilitated by various adaptions and processes, such as growth inhibition, sugar storage, increased hardiness, and, most well-known, leaf senescence (Willis, 2009).

Boreal forests generally experience colder temperatures than do temperate forests, often below freezing for much of the year, and are subject to shorter growing seasons (Gauthier *et al.*, 2015). Because conifers dominate these systems, forests are mainly evergreen and lack the leaf-senescing character of temperate forests (Neale and Wheeler, 2019). There is no sharp separation between temperate and boreal forests, and the two types often overlap, with broadleaf species often occupying more-fertile sites and conifers less-fertile sites. Secondary factors promote diversity across the biomes, leading to localized population and species differentiation (Esseen *et al.*, 1997). Both boreal and temperate forest tree species exhibit lower population differentiation than tropical forests,

BOX 5.
Genetic diversity and change in Australia's biomes

Australia comprises a unique mixture of forests and shrublands. It is home to tropical forests in the north, shrublands and temperate forests in the south, and a sizeable arid zone in the centre (Keith *et al.*, 2020). Australian plant species have a relatively independent evolutionary history compared with the rest of the world (although they share many Gondwanan relicts with South America, such as *Nothofagus* and *Araucaria*). Nevertheless, Australian plants exhibit general trends in genetic diversity dictated by life-history traits (as outlined above), with those with higher abundance, larger ranges and greater continuity displaying higher levels of genetic diversity.

The Australian tropical–subtropical biome in the north and northwest consists mainly of seasonal forests. Previously widespread, aseasonal tropical rainforests have steadily contracted in the last 20 million years and are now present only in isolated pockets (refugia) on the continent's northeast coast (Pennington *et al.*, 2004).

Eastern and western Australia consist of two distinct biomes, temperate and Mediterranean (which transition into shrubland towards the arid centre). Genetic diversity is highest in the temperate biome, likely due to several factors (Broadhurst *et al.*, 2017). Aridification in Australia began in the mid-Miocene, around 15 million years ago, but fully arid landforms in central Australia appeared much later, around 1–4 million years ago (Byrne *et al.*, 2008). Aridification pushed the two biomes towards the continent's edges, although this was less pronounced in the temperate biome. In addition, a more varied topography allowed certain species to escape this by moving south or upwards in altitude, which preserved genetic diversity (Byrne *et al.*, 2008). Trees make up the majority of plant species in the temperate biome, in contrast to the Mediterranean biome, which has a more significant proportion of shrubs. In Australia, shrubs have been shown to have less genetic diversity than trees, which is unusual because, in other biomes, shrubs and trees have been found to exhibit similar levels of diversity. The discrepancy in Australia may be due to the more localized distribution and smaller ranges of Australian shrubs.

The higher differentiation in Australian trees compared with other continents, leading to more localized and genetically distinct populations, is likely driven by two factors. The first is the more significant fraction of insect- and wind-pollinated trees in Australia, which have a relatively low range of pollen dispersal (Gamba and Muchhala, 2020). The second is habitat fragmentation, which is assumed to be more widespread in Australia than elsewhere (Broadhurst *et al.*, 2017). This understanding is important for conservation: genetic studies can be used to inform efforts such as seed banking, and recent human-mediated fragmentation means that some Australian tree species may be more susceptible to habitat destruction caused by human activities.

Sources: **Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G.** 2022. A function-based typology for Earth's ecosystems. *Nature*, 610(7932): 513–51; **Pennington, P. T., Cronk, Q. C. B., Richardson, J. A., Crisp, M., Cook, L. & Steane, D.** 2004. Radiation of the Australian flora: what can comparisons of molecular phylogenies across multiple taxa tell us about the evolution of diversity in present–day communities? Philosophical Transactions of the Royal Society of London. Series B: *Biological Sciences*, 359(1450): 1551–1571. doi: 10.1098/rstb.2004.1528; **Broadhurst, L., Breed, M., Lowe, A., Bragg, J., Catullo, R., Coates, D. *et al.*** 2017. Genetic diversity and structure of the Australian flora. *Diversity and Distributions*, 23(1): 41–52. doi: 10.1111/ddi.12505; **Byrne, M., Yeates, D. K., Joseph, L., Kearney, M., Bowler, J., Williams, M. A. *et al.*** 2008. Birth of a biome: insights into the assembly and maintenance of the Australian arid zone biota. *Molecular Ecology*, 17: 4398–417. doi: 10.1111/j.1365-294x.2008.03899.x; **Gamba, D. & Muchhala, N.** 2020. Global patterns of population genetic differentiation in seed plants. *Molecular Ecology*, 29: 3413–3428. doi: 10.22541/au.158022653.32078930 facilitated by large population sizes and ranges, along with the dominance of wind pollination, which ensures extensive gene flow (Gamba and Muchhala, 2020).

The retreat of temperate and boreal forests into refugia during the Last Glacial Period and their expansion when the period ended are features in both the Northern and Southern hemispheres and have influenced modern-day genetic diversity in these forests. A typical pattern can be observed in locations where populations of higher genetic diversity cluster around areas corresponding to past refugia. In contrast, genetic diversity decreases with distance from these locations due to founder effects caused by individuals re-colonizing land previously under ice and radiating out with a smaller fraction of the total diversity of the species (Tzedakis *et al.*, 2013). Species that had high numbers of ice-age glacial refugia, which also had a more extensive past range, have been shown to have higher levels of genetic diversity today than those with fewer glacial refugia (Roberts and Hamann, 2015). Box 5 discusses change over millennia in Australia's temperate and Mediterranean biomes and how this has influenced genetic diversity there.

5.7 Conclusions

Predicting the level and distribution of genetic diversity in forest tree species is complex because of interactions in the forces that shape these. Rossetto *et al.* (2020) demonstrated that genetic structure and diversity can differ across the same landscape among different species within a single genus, and they suggested that large-scale, multispecies comparisons can reveal informative patterns in the genetic diversity of trees and woody plant species. Forest trees generally have higher within-population genetic diversity, lower genetic differentiation and lower levels of inbreeding than other plants (Cavers and Cottrell, 2015; Petit and Hamp, 2006; Hamrick and Godt, 1996; Hamrick, Godt and Sherman-Broyles, 1992) because of ecological and life-history traits such as:

- greater population range and size;
- far-reaching pollination/seed-dispersal mechanisms such as wind and animal ingestion;
- tendency to favour outcrossing; and
- longevity, with overlapping generations.

Numerous external forces can reduce the genetic diversity of tree species, including those that are a direct result of human activities. Habitat clearance can fragment populations and reduce diversity, especially in bird- or insect-pollinated trees (Ward *et al.*, 2005), and climate change may affect tree species in myriad ways, such as by changing ecological and selective pressures and fragmenting and reducing their range (Lyam *et al.*, 2022). Understanding how these factors influence genetic diversity and managing them to reduce their negative impacts is essential for successful FGR conservation.

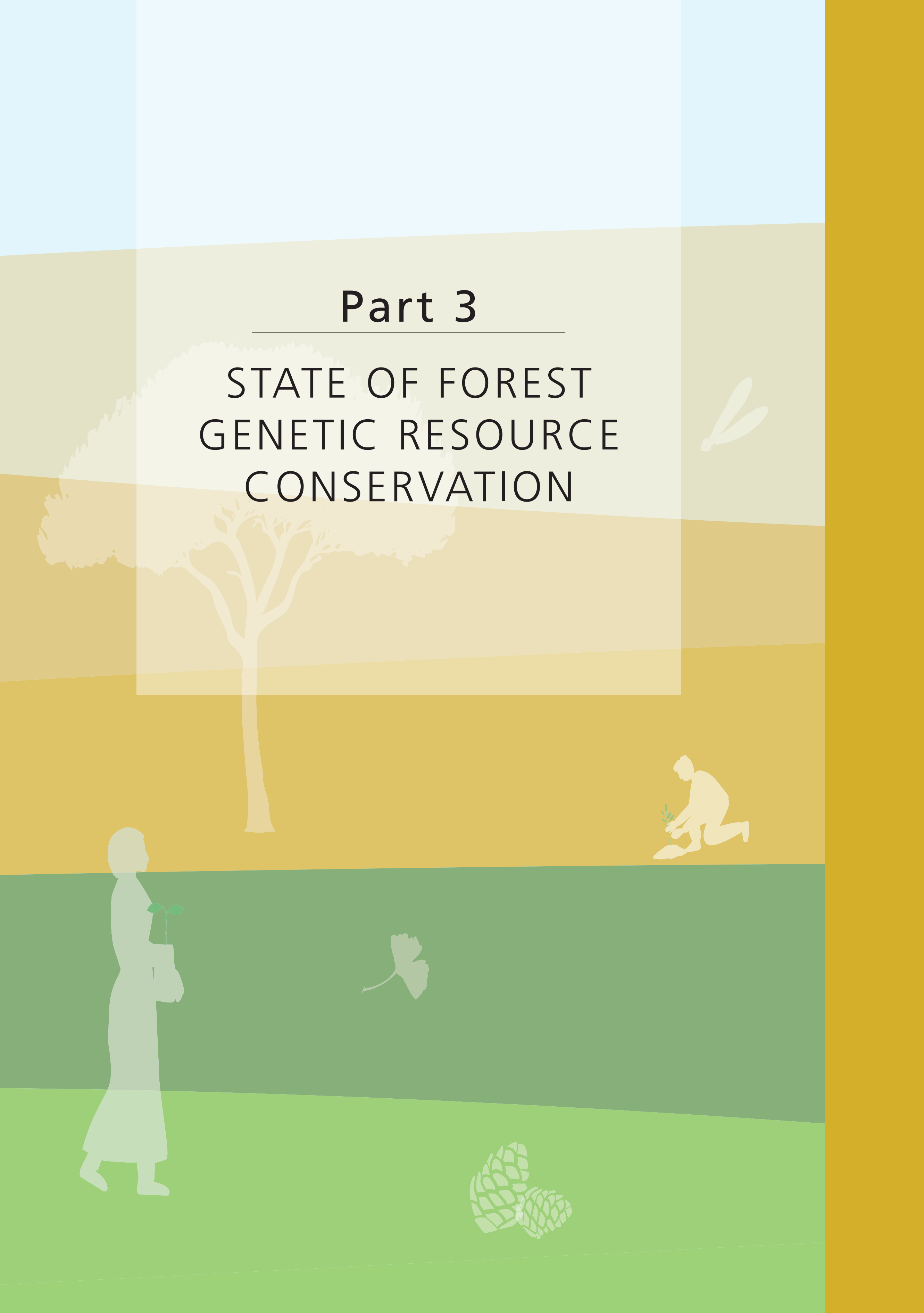
The loss of genetic diversity in trees and other woody plants continues, especially in the tropics and subtropics. Rare and threatened species worldwide are particularly exposed to genetic erosion. The Global Plan of Action urged countries to establish and strengthen national FGR assessment, characterization and monitoring systems (FAO, 2014b), but country reports indicate that progress on this has been limited. Provenance trials are crucial for non-molecular characterization, and countries have maintained existing trials and are establishing new ones. Many studies have been carried out in the last decade to characterize genetic diversity using molecular techniques, increasing the number of species for which genetic data are available, but a small proportion of the world's tree and other woody species have been genetically characterized with either molecular or phenotypic analysis. A few countries have established genetic monitoring systems to track temporal changes in genetic diversity, but these systems are still in their infancy, and practical methodologies are still being developed and tested.

The limited effort to monitor genetic diversity is not unique to trees and other woody plants. Hoban *et al*. (2021a) reviewed how Parties to the

CBD report on genetic diversity and found that they rarely mention genetic monitoring over time, indicating a considerable gap in implementation of the CBD. Hoban *et al*. (2021a) also noted that countries emphasize *ex situ* conservation and legislation in their reporting. This is probably an unintended consequence of the narrowly formulated genetic indicators of the earlier Aichi Biodiversity Targets, which focused only on the genetic resources of crops and livestock. The Kunming–Montreal Global Biodiversity Framework recalls the importance of conserving the genetic diversity of all species and includes a headline indicator on genetic diversity (A.4 – "the proportion of populations within species with an effective population size > 500") in its proposed monitoring framework. This indicator is based on the proposal by Hoban *et al*. (2020), who also stressed the need to monitor genetic diversity with DNA-based methods due to the depth of information these methods can provide around allelic diversity, effective population size, and the potential for species to adapt to environmental changes. However, no indicator based on molecular methods will likely be included in the new monitoring framework to be agreed by the CBD because it would be a potentially difficult and resource-intensive shift away from the broader biodiversity metrics (e.g. species counts) traditionally used. Nevertheless, the efforts of countries to manage their FGR would benefit from establishing and strengthening genetic monitoring systems based on molecular methods for target species that exhibit broad ranges of key characteristics, such as economic importance, endangered status, life history, reproductive traits, and distribution. In addition to genetic monitoring, management actions targeting genetic diversity are crucial for halting its further decline (Shaw *et al*., 2025).

Part 3

STATE OF FOREST GENETIC RESOURCE CONSERVATION



Chapter 6

In situ conservation of forest genetic resources

6.1 Introduction

For FGR, *in situ* conservation refers to the genetic conservation of tree and other woody plant species in their natural environments by targeting individual populations of these species (FAO, 2014a) with the aim of maintaining or increasing their evolutionary and adaptive potential using natural selection as a driver. *In situ* conservation is intrinsically dynamic because the populations maintain ecological interactions with other biota and undergo evolutionary processes such as natural selection, genetic drift, and gene flow and mutation (FAO, 2014a). *In situ* conservation is also the most efficient option for conserving the gene pools of tree species (Kelleher, 2018) because its cost is lower per unit of genetic diversity than that of *ex situ* conservation (Gapare, 2013).

The *in situ* conservation of FGR is carried out typically in protected areas and managed forests (FAO, DFSC and IPGRI, 2001) and in forest reserves or stands designated specifically for the genetic conservation of a given species (FAO, 2014a). An important aspect of *in situ* conservation is that it does not exclude the use of conserved resources. It maintains the ecological, aesthetic, ethical and cultural values of species and simultaneously allows the genetic conservation of multiple species.

Genetic reserve of small-leaved lime (*Tilia cordata*) in Finland

© FAO/Jarkko Koskela

SoW-FGR1 found that countries interpreted the concept of *in situ* conservation in different ways and that only about 1 000 species were conserved *in situ* for their genetic resources (FAO, 2014a). The Global Plan of Action called for the strengthening of *in situ* FGR conservation and increasing the number of priority species to be targeted for its application (FAO, 2014b). This chapter examines approaches for the *in situ* conservation of FGR and presents its present state based on country reports. The chapter also reviews recent scientific and technological advances supporting the *in situ* conservation of FGR in practice. Organizational aspects of *in situ* conservation are addressed in Chapter 11.

6.2 Approaches for conserving forest genetic resources

Conservation priorities defined with and without genetic information

Ideally, *in situ* FGR conservation is based on genetic knowledge of the targeted ecosystems and tree species and on their management through a properly designed network of genetic conservation areas (FAO, DFSC and IPGRI, 2001). Successful *in situ* conservation programmes require a clear definition of objectives, such as the maintenance of evolutionary processes and the sustainable use of, and long-term access to, the conserved resources.

The principles guiding *in situ* FGR conservation that were developed in the 1980s (e.g. Ledig, 1986) are generally still valid. The approach taken depends on whether conservation priorities are established based on genetic information or this information is unavailable. In the former situation, priorities can be defined by assessing the contributions of specific populations to the total neutral genetic diversity of a target species (Petit, El Mousadik and Pons, 1998). In the latter, which is the case for most tree species (see Chapter 5), ecological, geographical and plant demographic information can be used as proxies for genetic variation (e.g. Hamann *et al*., 2005; Koskela *et al*., 2013).

Genecological approaches have commonly been used in the past (Graudal *et al.*, 2014) to develop genetic conservation plans on the assumption that the distribution of genetic variation parallels patterns of ecological variation. For example, gaps in FGR conservation in British Columbia, Canada, were identified using variation in macroclimates as a proxy for adaptive genetic variation (Hamann *et al.*, 2005; Wang *et al.*, 2020). It should be noted, however, that the distribution of useful plant species may have been influenced by ancient and ongoing human management (Levis *et al*., 2017): for example, some plant populations show clear signs of domestication despite growing in seemingly wild areas, and others have been introduced to areas where they did not occur naturally (e.g. Thomas *et al*., 2012). For such species, it may be more appropriate to develop cultural-ecological proxies to spatially characterize their genetic variation.

Climatic stratification (Metzger *et al*., 2013) has been used to develop a pan-European network of genetic conservation units (de Vries *et al*., 2015) by identifying a minimum set of conservation units distributed across climatic zones and countries representing the genetic variability across the target tree species' distribution. Should genetic information become available for the target species, it could be used to further refine the network of genetic conservation units (e.g. Scotti-Saintagne *et al*., 2024).

The primary target for conservation should be adaptive genetic diversity (i.e. genetic variation under natural selection) because of its long-term importance, but this has generally been neglected in conservation planning because of the difficulty of measuring it directly. Common gardens, which are experiments designed to quantify genetically based phenotypic differentiation comparing native with introduced tree populations, typically provide this type of information; however, these are available for only a few species of high economic value. Advanced genotyping and sequencing techniques, combined with improved statistical methods, are providing tools by which adaptive genetic diversity can be estimated more easily, thereby facilitating large-scale analyses. Teixeira and Huber (2021) suggested that, to develop effective genetic conservation strategies, it is necessary to understand functional genetic diversity (i.e. genetic diversity at specific loci controlling functional traits responsible for adaptation), demographic history and ecological relationships. In contrast, DeWoody *et al.* (2021) presented arguments in favour of assessing neutral genetic diversity (i.e. genetic variation that is selectively neutral) because it is tied closely to evolutionary fitness. Other authors have suggested that, in addition to genetic variation, gene flow and selection play key roles in determining whether a population can adapt to environmental change (e.g. Aravanopoulos, 2016).

Fernandez-Fournier, Lewthwaite and Mooers (2021) tested whether standing genetic variation[13] could be used as a proxy for adaptive genetic variation in lodgepole pine (*Pinus contorta*) in western Canada. They found that priority populations identified for conservation based solely on adaptive variation were not significantly divergent from populations identified through genome-wide genetic variation. The authors concluded that a simple analysis of mean genome-wide genetic variation would enable the identification of local adaptation and the setting of priorities accordingly. Under conditions in which fragmentation and bottlenecks occur and drift overwhelms selection, both neutral and adaptive diversity would be similarly affected. This means that, for species of high concern, there is no need to pursue the identification of adaptive variation as a mandatory step before defining priority populations.

Ottenwell *et al.* (2016) proposed identifying priority populations based on a combination of genetic parameters such as population differentiation, genetic diversity and inbreeding, measured for the populations of conservation concern and for representative "healthy" populations as a reference. Other authors have suggested accounting for both key neutral and adaptive components of genetic diversity in complementary ways (Funk *et al.*, 2012; Rodriguez-Quilon *et al.* 2016) for the identification of genetic conservation units, particularly in tree species showing marked population structures and complex evolutionary histories.

Species and spatial conservation priorities

For FGR conservation, delineating species and genetic groups within species is an essential step. Recent research has enabled the better approximation of taxonomic boundaries (particularly in Africa; see, for example, Daïnou *et al.*, 2017; Ahossou *et al.*, 2020; Ewédjè *et al.*, 2020) and improved understanding of the natural histories of tree species.

Research on genetic diversity has focused traditionally on species with economic value or iconic status (e.g. Wehenkel *et al.*, 2017), leaving major gaps in the conservation of many threatened tree species (e.g. imperilled oaks in the United States of America; Backs and Ashley, 2021). Nevertheless, a growing number of studies have focused on rare, endemic and threatened tree species with small and isolated populations (e.g. Tamaki, Setsuko and Tomaru, 2016; Quiñones-Pérez, González-Elizondo and Wehenkel, 2017), providing important insights given that species with small and isolated populations tend to be more exposed to the impacts of genetic drift and inbreeding (Jaramillo-Correa *et al.,* 2009). It is also important to assess the amount of genetic diversity in conserved populations. In Mexico, which has the world's highest diversity of pine and oak species, a recent review of existing FGR conservation efforts revealed a very poor representation of genetic diversity (Wehenkel *et al.*, 2017). Regarding spatial conservation priorities, marginal populations deserve particular attention in FGR conservation, especially

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[13] Standing genetic variation is the diversity of the initial gene pool before the action of natural selection acting upon it. In other words, it is the presence of alternative forms of a gene (alleles) at a given locus in a population; it is the diversity of choices on which selection pressures operate.

rear-(warm)-edge marginal populations, which are exposed to warmer temperatures and are considered more susceptible to warming than populations at the centre of a species' range (Fady *et al*., 2016).

6.3 State of *in situ* conservation of forest genetic resources

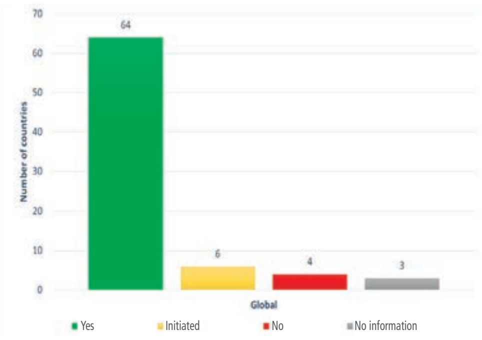
SoW-FGR1 found that countries interpreted *in situ* FGR conservation in different ways, ranging from conservation in protected areas with limited or no intervention to active genetic conservation, in which management actions are carried out to facilitate natural regeneration and mitigate biotic and abiotic threats (FAO, 2014a). For the present report, countries were invited to report on whether they have national *in situ* conservation systems in place for FGR (and if so, the establishment year), and the area (in hectares) and number of *in situ* conservation units, by species, included in such systems. SoW-FGR1 reported only the number of species under *in situ* conservation and therefore comparisons between the two assessments are possible only for this variable.

Of the reporting countries for the present assessment, 83 percent (64) indicated that they have operational national *in situ* conservation systems (see annex), and six additional countries reported that they had initiated the establishment of such systems (Figure 10). The number of countries with operational *in situ* conservation systems has increased by 10 percent since 2012, when the number was 58 (Luxembourg, Malta, Mexico, Panama, Spain and Sweden were the additions). Six reporting countries were unable to indicate the establishment year of their *in situ* conservation systems (it was assumed in the analysis that these countries already had their systems in place in 2012).

The most common components of the *in situ* conservation systems were protected areas (reported by 54 countries), followed by *in situ* FGR conservation units (52 countries), and forests managed for the production of wood and/or non-wood products (41) (Figure 11). Four countries reported that other components (e.g. permanent monitoring or research plots and sacred forests) were included in their *in situ* conservation systems.

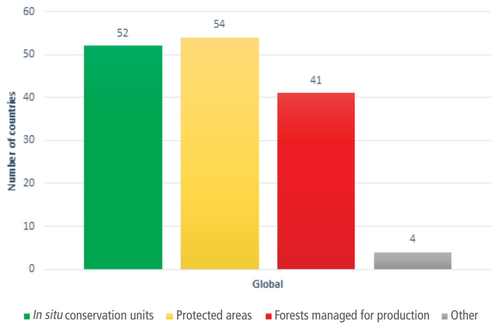
The reporting countries indicated a total of 35 114 *in situ* units collectively covering more than 533 million ha. These figures overestimate

FIGURE 10
Number of countries reporting the existence of operational national *in situ* conservation systems



Note: Based on country reports.

FIGURE 11
Number of countries reporting the existence of various components of national *in situ* conservation systems



Note: Based on country reports.

TABLE 11

Number of species, by region, included in *in situ* conservation programmes

Region	Number of species*
Africa	158
Asia	336
Europe	207
Latin America and the Caribbean	576
Near East	36
North America	117
Southwest Pacific	47

Notes: * Net number of species reported by the region. Based on country reports.

the actual number of units and the area covered because multiple species are typically conserved within a single unit, especially in the tropical biome (i.e. countries may have reported the same unit for several species). In total, the reported *in situ* conservation programmes encompassed 1 387 species, which is about 2 percent of the world's tree and other woody species. The number of species targeted by *in situ* conservation programmes ranges from 36 to 576 (Table 11). The total number of species covered by *in situ* conservation is likely to be much higher than indicated because species other than those specified in country reports are likely to benefit from protection in *in situ* conservation units.

Protected areas play a dominant role in *in situ* FGR conservation in many countries, although they are typically not established for this purpose but, rather, for conserving forest habitats or charismatic species. In Australia, the total area in *in situ* FGR conservation is 46.0 million ha, consisting of native forests managed for the protection of biodiversity through either formal or informal mechanisms. Canada indicated that 29.5 million ha of forests is in various protected areas and that these areas were mostly established for purposes other than conserving FGR. In the reporting countries, the area in *in situ* FGR conservation areas was typically much smaller than the total area of protected areas. This suggest that countries lack specific information on tree and other woody plant species (e.g. the extent of occurrence and population sizes) in protected areas and that the contributions of these areas to FGR conservation are inadequately documented and recognized.

Although protected areas often form the backbone of *in situ* FGR conservation, most countries also have other areas designated for this purpose. In China, the *in situ* conservation system is based on forest reserves covering more than 20 million ha, but the country has also established 51 genetic conservation forests for more than 40 tree species since 2003. In Poland, the *in situ* conservation system builds on forests in national parks (195 200 ha), nature reserves (109 200 ha), genetic conservation stands (3 550 ha) and selected seed stands (15 170 ha). In their reports, many countries noted that valuable populations of trees and other woody plant species are found outside protected areas. This highlights the importance of establishing specific conservation stands and conserving FGR in managed forests and other suitable areas (as discussed further in section 6.4).

Protected areas play only a limited role in some countries or have no role at all in *in situ* FGR conservation systems. In Finland, valuable FGR do exist in protected areas, but these areas are not part of the FGR conservation programme because it is often not possible to include genetic aspects in their management. Instead, the country's *in situ* conservation system relies on gene reserve forests (totalling 7 218 ha), which are designed and managed for the genetic conservation of commercial and rare tree species. In Sweden, large areas of forests are in national parks and nature reserves but, as in Finland, these areas are not considered to fulfil the requirements for *in situ* FGR conservation. One reason for this is that tree populations are neither assessed, documented nor managed because genetic conservation is not a management objective in these protected areas. In its report, Sweden also noted that genetic conservation in nature reserves is hampered by restrictions in the Swedish environmental code and other national legislation. Therefore, genetic conservation units of forest trees have been established in habitat protection areas, which are defined in the country's legislation as "small land or water areas that are important environments for threatened plants or animals, or especially important to protect for other reasons".

These findings show that countries continue to interpret and implement *in situ* FGR conservation in different ways. This inevitably also affects the way in which countries gather data on their efforts. For future global FGR assessments, it will be necessary to continue work to harmonize the views of countries on *in situ* FGR conservation.

In their reports, countries raised concerns about various challenges expected to affect *in situ* FGR conservation or which are already having an impact (see also Chapter 10). These include deforestation and forest degradation, climate change, fire, insect pests and pathogens, invasive species and unsustainable harvesting. An additional challenge mentioned by many countries is securing or increasing human and financial resources dedicated to *in situ* FGR conservation, as well as the scientific skills and capacity needed to support this work.

Climate change was the most referred-to concern in the country reports, and several countries noted that traditional *in situ* FGR conservation may need support from additional actions such as assisted migration and *ex situ* conservation. The interdependence of countries in *in situ* FGR conservation may also increase, with the conservation of gene pools in one country supplemented by similar efforts in other countries. International and regional collaboration is expected to become even more crucial for ensuring *in situ* FGR conservation. Many country reports noted the need to deepen understanding of the impacts of climate change on forests and their ability to adapt and to increase knowledge of the spatial distribution of genetic diversity through range-wide studies that encompass a broad range of species.

6.4 *In situ* conservation planning and implementation

Ideally, *in situ* FGR conservation is implemented through networks of conservation units distributed across ecological zones and genetic lineages within a species' distribution range, with the effect of comprehensively representing the habitats occupied by the species and its underlying genetic diversity (de Vries *et al.*, 2015). Such an approach has the best chance of meeting economic, social and ecological objectives (Potter *et al*., 2017). Conservation planning should assess the overall genetic variation across the distribution range of the target species (Crandall *et al.,* 2000) and, on this basis, select representative stands and populations for inclusion in a network of genetic conservation areas. The minimum adequate size of conservation units varies depending on the goals of management (e.g. whether targeting low-frequency genes; Yanchuk, 2001) and the demographic characteristics of the targeted tree species. Generally, the size of the unit that needs to be conserved depends on the density of reproducing trees of the target species to ensure minimum effective population sizes (Frankham, Bradshaw and Brook, 2014) – thus, it can vary from a few to many thousands of hectares (FAO, DFSC and IPGRI, 2001).

Effective population size (Ne) has important practical applications in conservation genetics because it defines the rate of genetic drift and loss of genetic variability in a population. Thresholds values for Ne have been proposed ranging from 50 to more than 1 000, above which it is possible to maintain evolutionary potential in populations and prevent inbreeding depression and genetic drift (Franklin, 1980; Soulé, 1980; Frankham, Bradshaw and Brook, 2014; Hoban *et al*., 2020). Target 4 of the Kunming–Montreal Global Biodiversity Framework includes an indicator related to Ne for monitoring genetic diversity and nominates a threshold value for Ne of 500 to prevent genetic loss (CBD, 2022). As a rule of thumb, Ne corresponds to around one-tenth of the census size; thus, a value of

Ne=500 means a census size of around 5 000 individuals (Hoban *et al.*, 2023). The suitability of Ne as an indicator of genetic diversity is under debate (Fady and Bozzano, 2021; Santos del Blanco *et al.* 2022; Hoban *et al.*, 2021b).

The role of protected areas, managed forests and trees on farms

In their reports, many countries indicated that *in situ* FGR conservation is implemented in protected areas containing naturally regenerating wild populations, but it can also be achieved in managed production forests (e.g. timber concessions) and multiple-use forests (e.g. community-managed forests) (FAO, DFSC and IPGRI, 2001). Given that protected areas are becoming increasingly isolated by habitat fragmentation (Hannah *et al.*, 2007) and tend to be concentrated in upland areas that are less suited to agriculture, the gene pools of many species are located outside protected areas. For example, a recent study showed that, for 63 socioeconomically important tree species in Southeast Asia, 74 percent of the most important populations for *in situ* conservation were outside protected areas (Gaisberger *et al.*, 2022a). Similar results were reported by Ceccarelli *et al.* (2022) for socioecologically important tree species in Central Africa and by Fremout *et al.* (2020) in dry forests in southern Ecuador and northern Peru. *In situ* FGR conservation in protected areas needs be complemented by conservation efforts in other forested areas, including on communal lands and in agricultural landscapes and naturally regenerating production forests (i.e. where management is directed towards maintaining natural regeneration) and by setting aside representative forest areas for genetic conservation. Other tree-based systems (e.g. agroforestry) and trees in domesticated landscapes (e.g. farms and homegardens) should also be targeted for FGR conservation efforts (Chirwa *et al.*, 2008; Dawson *et al.*, 2013).

In situ FGR conservation outside protected areas may involve land under diverse ownership, management and use regimes. Guo *et al.* (2022) used a database of more than 46 000 tree species to assess the extent of range protection and the level anthropogenic pressures to develop conservation priorities. They showed that a large proportion of tree species receive only limited protection in existing protected areas and that a large proportion of their range is under considerable human pressure (Guo *et al.*, 2022). A spatially explicit regional assessment of the main threats (i.e. overexploitation, fire, overgrazing, habitat conversion and climate change) to forest ecosystems, focusing on socioeconomically important tree species in Asia, showed that about two-thirds of the most important areas for their conservation were outside protected areas (Gaisberger *et al.*, 2022a). The study also identified natural areas in Borneo rainforests as important hotspots for *in situ* FGR conservation, which are also largely (82 percent) outside protected areas. Another study, based on a similar methodological approach and focusing on 16 important food tree species in Burkina Faso, found little overlap between protected areas, the co-occurrence of the targeted species, and the severity of threats to those species (Gaisberger *et al.*, 2017). In Asia, a study of three valuable rosewood species (*Dalbergia cochinchinensis, D. cultrata* and *D. oliveri*) found a high level of threat to these species, even in protected areas (Gaisberger *et al.*, 2022b).

The presence of tree species outside forests, such as in farmlands where species of interest previously occurred as part of natural forests or woodlands and now grow as planted or remnant trees (sometimes called *circa situm* or near-site conservation or farmer-based conservation), has been shown to play a significant role in linking vegetation remnants in heavily modified or fragmented landscapes, especially in tropical and subtropical areas (Boshier, Gordon and Barrance, 2004; Dawson *et al.*, 2013). The *circa situm* conservation approach is implemented in modified agricultural landscapes outside natural habitats occupied by a species but within its native geographic distribution. A recent literature review found high tree species richness in agroforests in

20 countries in the tropics and subtropics, linked primarily to the occurrence of native trees but with exotic trees often represented at higher densities (see Table 6 in Chapter 3). In Argentina, a new framework integrates livestock production with forest management to co-produce ecosystem services; in this framework, the conservation of native forests and their biodiversity is carried out in a way that allows low-impact productive activities, thereby balancing ecosystem integrity, production and the provision of services for the well-being of communities (Peri *et al*., 2022). The framework is intended to guide the identification of economic and ecological thresholds to achieve a balance between production and conservation.

The implementation of *in situ* strategies for FGR conservation is more challenging in high-poverty areas, where many users may depend on forest resources for their livelihoods and reconciling conservation and livelihood objectives is more difficult. A conservation approach called "other effective area-based conservation measures" (OECMs) was introduced to be applied in areas where *in situ* biodiversity conservation is achieved mainly as a byproduct of management carried out for other purposes ("ancillary conservation") and where conservation is not the primary management objective ("secondary conservation"). The OECM concept includes areas that match the IUCN definition of a protected area ("primary conservation") but where local governance authorities prefer not to report the area as protected. The definition of OECM was agreed at the 14th Conference of Parties to the CBD in 2018. Many countries are yet to start processes to identify OECM areas, although the compilation of a world database of OECMs has commenced (UNEP-WCMC and IUCN, 2023).

Socioeconomic aspects of *in situ* conservation

The consideration of socioeconomic aspects is important for the acceptability and success of *in situ* FGR conservation. In Europe, studies have shown that the public supports the strengthening of *in situ* FGR conservation through the designation of seed stands and conservation in protected areas (Šijačić-Nikolić *et al*., 2017) and a willingness to pay for research programmes on FGR, particularly those focusing on identifying resistance to biotic risks (Soliño, Alía and Agúndez, 2020).

Traditional land management systems, which are often based on culturally and ecologically sound management practices, can be effective in conserving FGR. In Brazil, Zechini *et al.* (2018) found no significant differences in genetic diversity of araucaria (*Araucaria angustifolia*) in populations managed as part of the traditional land-use system (including livestock management, the gathering of edible araucaria seeds, and woodfuel extraction) and populations in protected areas. Stoian *et al.* (2018) reported that forest concessions in the multiple-use zone of the Maya Biosphere Reserve in Guatemala generated socioeconomic benefits for local communities while also conserving high-value tree species (e.g. mahogany, *Swietenia macrophylla*), with deforestation close to zero. Traditional knowledge benefits both the conservation and use of FGR. Thomas *et al.* (2017) found that traditional harvesters of Brazil nut can estimate the annual seed production with the same accuracy as more expensive and labour-intensive measurements. Traditional knowledge has also been used to guide species selection in restoring tropical dry forests in Colombia (Fremout *et al*., 2021).

Groups and individuals with different social attributes, such as gender, wealth, age and ethnicity, often have different perceptions of the value of forests and differing access and use rights and motivations for conserving natural resources. Research on social aspects of FGR has attempted to characterize gender-differentiated knowledge, preferences and priorities of diverse social groups as well as priority species and their management (Carney and Elias, 2014; Elias, 2015; Elias *et al.* 2017; Karambiri *et al.*, 2017; Rimlinger *et al.*, 2021a,2021b; Gachuiri *et al.*, 2022). Focusing on the management and selection of shea-nut trees (*Vitellaria paradoxa*) in Burkina Faso, Carney and Elias (2013) showed that the knowledge of women and men for the same resource may be dissimilar due to differing access rights and use of local plants. Karambiri *et al.* (2017) showed that classification systems and preferences for shea varieties vary between gender and ethnic groups. Rimlinger *et al.* (2021a) described how perceptions, preferences and management practices on the intraspecific variability of an emblematic African fruit tree species (*Dacryodes edulis*) are shaped by ethnic and rural–urban differences.

6.5 Scientific advances supporting *in situ* conservation

Threat assessments

Spatial threat analyses have been conducted for a growing number of tree species to support *in situ* FGR conservation and help define priorities. Various studies have also advanced methods for assessing the exposure of tree species to threats at the habitat level and analysing species-specific sensitivity and vulnerability to threats. Overall, these studies have shown that large parts of the ranges of many tree species are exposed to significant threats and that habitat conversion and overexploitation are more imminent threats than climate change.

In Africa, Gaisberger *et al.* (2017) modelled, at a fine scale, the impacts of climate change and other threats (overexploitation, overgrazing, fire, cotton production and mining) on 16 tree species in agroforestry parklands in Burkina Faso. All species face serious threats throughout their ranges in the country, with overexploitation and cotton production the most important short-term threats and climate change the main longer-term threat (Gaisberger *et al.*, 2017). Ceccarelli *et al.* (2022) examined the distribution of 100 socioeconomically important tree species in Central Africa and the spatial extent of the main threats (climate change, fire, habitat conversion, overexploitation and overgrazing) to these species. They found that the species are vulnerable to all five threats; on average, about one-third (34 percent) of the distribution of the 100 species have high to very high vulnerability (Ceccarelli *et al.*, 2022).

Similar threat assessments have been carried out in Asia. Gaisberger *et al.* (2020) identified overgrazing and overexploitation as the two most important short-term threats to wild and cultivated populations of common walnut (*Juglans regia*) in three Central Asian countries (Kyrgyzstan, Tajikistan and Uzbekistan). In Southeast Asia, Gaisberger *et al.* (2022b) assessed the vulnerability of three valuable rosewood species (*Dalbergia cochinchinensis, D. cultrata* and *D. oliveri*) to threats across their native ranges in six countries in the Greater Mekong Subregion and found that all three species face significant threats in more than 75 percent of their native ranges, including in protected areas. Overexploitation was the single most important threat to these rosewood species, followed by habitat conversion and fire.

In South America, Van Zonneveld *et al.* (2018) analysed threats at the intraspecific level to 80 socioeconomically important tree species and found that about 60 percent of the populations of these species were threatened with extirpation. Fremout *et al*. (2020) focused on the 50 most common tree species in tropical dry forests in northwestern Peru and southern Ecuador and found that, on average, 46 percent of the distributions of these species were vulnerable to at least one threat and that, for most of the studied species, habitat conversion, overexploitation and overgrazing were more significant threats than climate change.

The above-mentioned studies show that, although climate change is a less-imminent threat to tree species and their populations than other pressures, it is crucial to take its impacts into account in FGR conservation.

Potter, Crane and Hargrove (2017) proposed dividing tree species into groups requiring specific types of management and conservation strategies for maintaining their adaptive genetic variation. The grouping can be done based on risks related to a species' exposure, sensitivity and capacity to adapt to climate change (Foden *et al.,* 2013). Potter, Crane and Hargrove (2017) used this approach to prioritize 339 native tree species for conservation, monitoring, management and restoration across all forested lands in the contiguous United States of America (including Alaska). The same authors identified 35 species requiring immediate conservation intervention, 43 species requiring conservation assistance, and 69 species requiring close monitoring.

Threats posed by climate change

The impacts of climate change on forests include potential changes in species' ranges, composition, vulnerability to pests and diseases, adaptation, and growth (Alfaro *et al.*, 2014; Kelleher *et al.*, 2015). A significant amount of research has attempted to assess such impacts on individual tree species and existing *in situ* conservation efforts (Bower, Devine and Aubry, 2017; Lima *et al.*, 2017; Serra-Varela *et al.*, 2017) to identify ways to incorporate climate-change considerations into *in situ* conservation strategies.

The extent to which plant species can tolerate changing climatic conditions or avoid them through habitat shifts depends on their level of adaptive capacity or phenotypic plasticity. Analytical approaches to determining species-specific vulnerability may use various parameters, such as life-history traits, distribution, and pest and pathogen data, combined with consensus climate regional projections (Bower, Devine and Aubry, 2017); area-based approaches use habitat suitability models and spatially explicit future predictions of species' ranges (e.g. Chakraborty *et al.*, 2021).

Spatial models of expected climatic change can be used to improve conservation outcomes in the face of climate change. For example, Gray *et al.* (2017) tested a novel approach for identifying current and potential future within-species conservation gaps across the ranges of 54 forest tree species in western North America. Using models of species' distributions in relation to the location of protected areas and the expected pace of climate change, they predicted that interior and boreal tree species would be most vulnerable.

Spatial models have been improved by including the potential for species to extend their distributions beyond their present realized niches and recognizing that the physiological limits that shape these distributions could also change under climate change. Scoble and Lowe (2010) suggested incorporating neutral and non-neutral genetic diversity in the form of phylogeographic and landscape genetic data into species distribution modelling to improve climate-related conservation planning. Catullo, Ferrier and Hoffmann (2015) developed a general framework to include key parameters associated with physiological limits and adaptive evolution into spatial models of climate change. The integration of range-wide genomic data and climate models for two sympatric endangered rosewood species (*Dalbergia* spp.) found differential adaptive characteristics, with species-specific implications for *in situ* conservation (Hung *et al*., 2023). Benito Garzón *et al.* (2019) reviewed a new generation of species' distribution models that account for local adaptation and phenotypic plasticity and concluded that such models generally deliver a less alarming message than previous models of species' distributions under new climates and noted that phenotypic plasticity should help (to a considerable degree) some plant populations to persist under climate change.

Quantitative genetics experiments with rare plants in multiple environments have been valuable for measuring phenotypic plasticity and its heritability and the way in which evolution acts on favourable traits and simultaneously on others that may limit adaptation (Edwards, 2015). Alberto *et al.* (2013) reviewed the knowledge gained from 250 years of common garden experiments with trees and observed clinal variation along environmental gradients. Flanagan *et al.* (2018) argued that, in some circumstances, common garden experiments are more efficient for deriving information on local adaptation than studies based on genomic tools but noted that a problem is the timescale over which such field trials yield useful data. Hoban *et al.* (2016) also reported on the limitations of genomic tools in detecting the underlying genetic basis of local adaptation. On the other hand, Mahony *et al.* (2020) demonstrated that genomic data are useful when combined with phenotypic data and noted that genomic data can also work as substitutes for phenotypic data (when phenotypic trials cannot be established) in guiding the management of tree populations in the face of climate change.

Evidence shows that, in many organisms, including trees, most complex traits are polygenic and characterized by a genetic architecture determined by numerous loci, each showing a small effect. Studies of *Pinus strobus* (Rajora, Eckert and Zinck, 2016) and *Pinus pinaster* (de Miguel *et al.*, 2022), for example, examined the degree of polygenicity in fitness-related traits and their variation across environments and time. The findings on *Pinus pinaster* suggested that polygenic adaptation can occur rapidly, and this has implications for the capacity of natural tree populations to adapt to environmental changes. Future climate-change studies based on species' climate envelopes should incorporate a genetic component that takes into account the speed of genetic adaptation.

In situ conservation measures designed for climate change

Genetic diversity and evolutionary processes drive the continuous adaptation of tree species to changing conditions at multiple scales, from fine scale, to landscape, to ecoregion (Fady *et al.*, 2020). It is possible to support natural processes with assisted-adaptation measures and active management, aided by improving knowledge on genomic diversity and evolutionary mechanisms. In the face of climate change, *in situ* FGR conservation should be supported by management measures such as silvicultural treatments, the monitoring of natural regeneration and the vitality of conserved populations, the selection of conservation units that contain altitudinal and other ecological gradients, and assisted migration to establish tree populations better adapted to projected future climatic conditions in a given location (Kelleher *et al.*, 2015).

Christmas *et al.* (2016) reviewed constraints that plants may face in adapting to climate change – such as a lack of available space for migration, the rapidity of environmental change, a lack of connectivity in the landscape, compromised niche availability, poor dispersal ability and low phenotypic plasticity – and identified conservation approaches that would be most appropriate in different circumstances. These consisted mainly of *in situ* conservation that targeted genetic refugia and remnant populations, the creation of biodiversity corridors, assisted migration and gene flow, and translocation to novel suitable habitats. Concerns have been raised that the risk of introducing genetic variation to facilitate adaptation to climate change might outweigh the benefits (Aitken & Whitlock, 2013; Whiteley *et al*., 2015). New DNA sequencing technologies, however, can be used to detect local adaptation and identify preadapted genetic variants in source populations within the species' range that can be moved into recipient populations to increase their evolutionary potential and capacity to withstand drastic environmental change. This strategy seems to be more beneficial for trees than other organisms, given their long life and dispersal limitations (Aitken and Bemmels, 2016; Gugger *et al*., 2018).

Studies have analysed the implications of climate change for *in situ* conservation strategies in different tree species and locations. For example, Diniz-Filho *et al.* (2018) proposed strategies for cagaita (*Eugenia dysenterica*), a native fruit tree growing widely in the Brazilian Cerrado, given predicted climatic conditions; studies have also investigated endemic North American redwoods (Ahuja *et al.*, 2017) and Patagonian *Nothofagus* forests (Marchelli *et al.*, 2017), where hotspots of genetic diversity seem to coincide with convergence zones of species' expansion routes. In Europe, studies have been carried out in certain countries (e.g. Skrøppa and Fjellstad, 2017; Postolache *et al.*, 2019;

Šijačić-Nikolić *et al.*, 2019) and at the pan-European scale (Schueler *et al.*, 2014) to assess the vulnerability of dynamic genetic conservation units of forest trees to climate change. The establishment of additional genetic conservation units has been recommended in response to climate change (Kelleher *et al.*, 2015).

The genomic offset approach has been proposed to predict the possible future for tree populations. This uses genomic and environmental data to predict the optimal genetic composition of targeted tree populations that would enable them to adapt to modelled future environmental conditions and to determine the degree of potential maladaptation (defined as the "distance between the current and required genomic composition in a set of putatively adaptive loci"; Rellstab *et al.*, 2021). The approach has been applied in only a few cases, however, and requires further testing. An example is a study of Tibetan cypress (*Cupressus gigantea*) growing more than 3 000 m above sea level in the Qinghai–Tibet Plateau, which identified those populations most vulnerable to future climate change and delineated potential conservation units (Yang *et al.*, 2022).

Other authors have proposed the use of genomic prediction models to study the evolution of relict natural populations and then design conservation measures (Arenas *et al.*, 2021). These models, normally used in crop breeding to predict the occurrence of traits of interest and shorten the length of the breeding cycle, were piloted to predict the performance of introduced saplings of sacred fir (*Abies religiosa*) in a managed population of this species in Mexico. The preliminary results are encouraging, but Arenas *et al.* (2021) noted that genomic prediction models should be further tested in small, isolated natural tree populations.

Threats posed by pests and diseases

Forest health is an increasing concern due to the impacts of non-native insect pests and diseases and the expansion of native pathogens favoured by climate change (Holliday *et al.*, 2017). The management of pests and diseases is often neglected in FGR conservation goals, but the conservation of genetic diversity produces positive outcomes in reducing their impact. For example, conserving genetic diversity maintains high levels of overall population fitness and enhances the chances of finding individuals and populations able to resist specific pathogens. Herbivory by insects is more contained in species-rich forests and mixed versus monospecific stands, especially when phylogenetic distance among tree species is high (Jactel, Moreira and Castagneyrol, 2021). Phylogenetic distance generates a "dilution" effect on host species and consequently reduces the growth and spread of pathogens, particularly when these are not generalists (Keesing *et al.*, 2010). Diversity also has an indirect effect on resistance to pathogens because of the lower level of drought-related stress in high-diversity stands (Rasche, Fahse and Bugmann, 2013). Recent research using a dataset of more than 130 000 forest plots in the United States of America indicated, however, that two contrasting effects are simultaneously at play: non-native pest diversity increases with low-level tree diversity (facilitation effect) but is reduced at higher tree diversity (dilution effect) (Guo *et al.*, 2019).

Many forest tree species have some degree of genetic resistance to most pathogens and insects (Woodcock *et al.*, 2018). Screening intraspecific diversity in natural stands to explore its relationship with variation in resistance to pests and diseases is a strategy used for some tree species in recent decades. Screening is done today using advanced genomic tools, which can improve the way in which forest health problems are addressed (National Academies of Sciences, Engineering, and Medicine, 2019). New tree genomic resources have contributed to understanding of the genomic architecture of insect and disease resistance and to the development of both conventional breeding and genetic engineering (Naidoo *et al.*, 2019).

Ash dieback in Europe caused by the fungus *Hymenoscyphus fraxineus* has had a devastating impact on European ash (*Fraxinus excelsior*) populations across its range (Baral, Queloz and Hosoya, 2014; Enderle, Stenlid and Vasaitis, 2019) and on the *in situ* conservation of the species. Phenotypic and genotypic selection have been used to identify putatively resistant ash individuals, showing that genotypic selection is a faster approach than phenotypic selection (Chaudhary *et al.*, 2020) and that the disease resistance and tolerance traits of trees appear to be under the control of many genes, each of which has small effects (Sollars *et al.*, 2017). The polygenic nature of complex traits that confer resistance may limit the power of marker-supported selection. Nevertheless, genome-wide association studies can work in cases where disease resistance traits have simpler genomic architecture, as is the case for American beech (*Fagus grandifolia*), an ecologically important species in eastern North America, for which a major gene for beech bark disease resistance has been identified (Ćalić *et al.*, 2017). Another tree species of significant concern is Indian rosewood (*Dalbergia sissoo*), an important nitrogen-fixing and multipurpose tree planted worldwide. In the last two decades, the species has been under pressure from overexploitation and pathogens, mainly fungi that cause root rot and vascular wilt diseases (Shah *et al.*, 2021). Initial screenings have been conducted to identify resistant genotypes of Indian rosewood (Harsh, Chandra and Uniyal, 2011; Dobhal *et al.*, 2019).

New biotechnological tools have been developed to mitigate the effects of pathogens on forest trees such as American chestnut (*Castanea dentata*), a formerly dominant or co-dominant tree but now functionally extinct due to an invasive fungal pathogen. After several decades of research, blight-tolerant American chestnut individuals have been developed through genetic engineering to introduce a gene from wheat. This gene produces an enzyme that enables the tree to break down the oxalate produced by the pathogen (Steiner *et al.*, 2017; Powell *et al.*, 2019). This raises the question of whether traditional *in situ* conservation efforts are enough to safeguard FGR against future forest-health challenges. Genomic biosurveillance has been proposed as a new approach based on DNA signatures, which can be used to identify pests and pathogens, attribute detected samples to specific sources of pathogens, identify pathways that facilitate spread, and predict the invasiveness and pathogenicity of organisms (Bilodeau *et al.*, 2019; Hamelin and Roe, 2020). Such a system could reduce the speed of invasions. Ferrenberg (2016) noted that the influences of landscape features on pest dynamics and forest pest–host interactions will become more difficult to predict in rapidly changing environmental conditions.

New genetic, genomic and biotechnological tools for guiding conservation interventions

Range-wide assessments of genetic diversity and international research collaboration are important means for informing and guiding effective *in situ* FGR conservation in light of various threats. Despite major gaps in the intraspecific characterization of tree species, range-wide studies on genetic diversity of trees have grown significantly in the last decade, targeting an increasing number of tropical tree species. Examples include the characterization of the severely threatened species *Dalbergia cochinchinensis* in Asia (Hartvig *et al.*, 2020) and work on the taxonomic delimitation of *Khaya* spp. in sub-Saharan Africa (Bouka *et al.*, 2022). These use molecular markers to assist the identification of populations that host high or low levels of genetic variation and of lineages with unique traits that might be important for adaptation due to differential natural selection (Marchelli *et al.*, 2017; Potter *et al.*, 2017).

The growing number of studies on tree species' genetic diversity (see Chapter 5) suggests a need to synthesize results across the genetic marker systems used and identify new patterns not previously observed. Despite the many population genetic/phylogenetic studies on tree species in various regions, systematic reviews and meta-analyses are limited that bring these data together and support broader decision-making for specific regions. A meta-analysis conducted for ten tree species in eastern Africa (Dawson *et al*., 2017) found that most datasets showed a strong positive correlation between population pairwise genetic divergence and geographic distances, with generalizable methodological implications for tree genetic resource sampling to support conservation. The meta-analysis also suggested that site suitability and climate stability are positively related to population genetic diversity (Dawson *et al*., 2017), supporting current decision-making on priority areas for *in situ* conservation and restoration. Another meta-analysis based on 92 case studies (González *et al*., 2019) compared the impacts of habitat fragmentation and degradation on plant allelic richness and gene diversity (expected heterozygosity) and examined how these impacts varied across life-forms, lifespans, mating systems and commonness. The analysis found that long-lived trees and self-incompatible species are more liable to allelic richness loss than gene diversity loss. Moreover, tropical plant communities are more liable to allelic loss than temperate communities.

Genomic approaches have promise for assisting conservation practice (Segelbacher *et al*., 2022). Genome-wide data provide novel insights and can contribute to improve traditional conservation genetic inferences (Shafer *et al*., 2015; Plomion *et al*., 2016b; Neale and Wheeler, 2019). For Scots pine (*Pinus sylvestris*), genomic data from a relatively small number of adaptive genes confirmed the high level of differentiation and unusual evolutionary history of populations from Scotland (Wachowiak *et al*., 2011). In black cottonwood (*Populus trichocarpa*), an extensive genome scan revealed geographic differentiation patterns at different scales in western North America (Slavov *et al*., 2012). The use of genomic data has also assisted in clarifying issues related to taxonomic complexity, unrecognized clonality and hybridization, as in the case of two rare species of eucalypt, *Eucalyptus virginea* and the putative hybrid *E.* × *phylacis* (Bradbury, Binks and Byrne, 2021). Boundaries in sub-Saharan tree species have been delimited more efficiently and inference of phylogenetic relationships between species has improved (Dauby *et al.* 2014; Heuertz *et al.,* 2014). Genomic data have also advanced insights into inbreeding depression in natural populations (Kardos *et al*., 2016).

Approaches based on transcriptomic, proteomic and metabolomic data have been adopted to investigate highly complex traits (e.g. Depardieu *et al*., 2021). These methods, in combination with genome-wide variation data, enable the exploration of causal linkages between genotype and phenotype through statistical modelling (Marjoram *et al.,* 2014; Benestan *et al*., 2016). Despite such advances, however, the interpretation of genomic data is challenging and risks remaining in the research domain without having an effective influence on field practice (Shafer *et al*., 2015).

There has been significant progress in the last decade in the use of genomic data to examine the extent of local adaptation in individuals and populations (also of rare and endangered species; Funk *et al*., 2012), even on very short spatial scales (Neale and Wheeler, 2019). Although earlier attempts to explore local adaptation were based mainly on targeting candidate genes or finding neutral markers linked to adaptive loci, screening entire genomes now has much more power to unveil mechanisms that lead to evolutionary change, such as polygenic and epistatic selection (Plomion *et al*., 2016b; Neophytou *et al*., 2022). New technologies that span domains – from genetics, molecular biology and bioinformatics to machine learning and robotics – are enabling study of the structure, function and evolution of genes by means of high-throughput methods (van Dijk *et al*., 2021).

Evolutionary theory can provide answers to many conservation management questions (Eizaguirre and Baltazar-Soare, 2014). Adaptive introgression is the process through which new variations are incorporated in a population via gene flow from either the same or a different species and maintained by natural selection via increased fitness (Burgarella *et al*., 2019). Adaptive introgression can mitigate the consequences of limited adaptive potential associated with standing genetic variation and mutation and could enable a relatively fast response to changing environmental conditions (Hamilton and Miller, 2016; Suarez-Gonzalez, Lexer and Cronk, 2018). Advances in genomic tools have contributed to a better understanding of this phenomenon with the capacity to detect signatures of selection in introgression and link adaptive introgression to phenotypic variation and fitness through improved statistical techniques (Suarez-Gonzalez, Lexer and Cronk, 2018). These refined approaches allow the prioritization of conservation units to maximize evolutionary potential (Eizaguirre and Baltazar-Soare, 2014). Natural hybrid zones in forest trees have been targeted by research as model systems to analyse the transfer of adaptive genetic variation by introgression (Suarez-Gonzalez *et al.*, 2016; Menon *et al.*, 2021).

Increasingly high-quality information is being generated on the past population histories of tree species. Phylogeographic research has expanded considerably in the last decade through diverse studies on tree species' past refugia in different regions that could be considered as priorities for *in situ* conservation, also taking into account the spatial distribution of the main gene pools. Several such studies have been conducted on African tree species (e.g. Heuertz *et al.*, 2014; Hardy *et al.*, 2013; Monthe *et al.*, 2019; Piñeiro *et al.*, 2017, 2021) and on species in other regions (e.g. Cubry *et al.*, 2015; Piotti *et al.*, 2017; Zinck and Rajora, 2016; Walas *et al.*, 2019; Thomas *et al.*, 2015; Chen *et al.*, 2019). Multispecies phylogenetic studies have helped identify regions of high conservation value that harbour rare and highly divergent genetic assemblages and lineages (Cheikh Albassatneh *et al.*, 2021).

Landscape-level approaches show potential for addressing conservation and management questions (Keller *et al.*, 2015). Regional landscapes have an influence on local populations, but a key question is about the spatial scale of this effect and how it differs based on the type of response measured. Some authors have shown that the evolutionary history and heritage of taxa create regions with differential levels of genetic originality and distinctiveness (Cheikh Albassatneh *et al.*, 2021). Jackson and Fahrig (2014) showed the importance of managing large buffers around sites targeted for conservation because managing protected species at spatial scales based on population abundance may lead to the neglect of broader landscape effects on population genetic diversity and persistence. The identification of the spatial co-occurrence of landscape features and significant genetic discontinuities between populations reveals the spatial distribution of diversity and the divergence of populations (Chiocchini *et al.*, 2016; Mattioni *et al.*, 2017), with implications for the selection of priority sites for conservation. Ecological genomics is an interdisciplinary field that seeks to understand the responses of organisms to their natural environments by applying functional genomics to identify and characterize genes with ecological and evolutionary relevance (Ungerer, Johnson and Herman, 2008; Renn and Siemens, 2010; Holliday *et al.*, 2017; Lu, Loopstra and Krutovsky, 2019). Landscape genomics is another rapidly advancing multidisciplinary field of research that combines population genomics, landscape ecology and spatial analysis to assess the influence of environmental heterogeneity on neutral and adaptive genetic variation (Hand *et al.* 2015; Balkenhol *et al.*, 2017). A revived interest in gene flow and its capacity to counteract mutation, drift and selection, even at low intensities, is supported by new data-rich genomic techniques that enable a closer examination of the role of gene flow in plant evolution and how it varies according to species, the specific populations investigated, and within the same population over time (Ellstrand, 2014).

6.6 Conclusions

The guiding principles for *in situ* FGR conservation developed in the 1980s remain largely valid, with no major methodological shifts, but conservation efforts can now take advantage of advanced genomic tools that offer higher detection power. Compared with the situation reported in SoW-FGR1, notable progress has been made in the number of tree species targeted for *in situ* FGR conservation, and more countries have established national *in situ* FGR conservation programmes.

Threats to forest ecosystems may not result in species' extinctions but can lead to the loss of populations containing unique traits. Therefore, the proper characterization of intraspecific diversity and the implementation of conservation actions at the population level are crucial for many species. Since SoW-FGR1, genetic and genomic data for a wider range of species have become available, and comprehensive assessments of tree species genetic diversity are improving understanding of where to focus *in situ* conservation efforts. Nevertheless, proper genetic characterization is missing for a large number of species and, given the unique biological features of each species, their genetic diversity has idiosyncratic patterns.

Recent spatial analyses have shown that only a small proportion of tree species genetic diversity is included in protected areas, underscoring the need for *in situ* conservation strategies that incorporate multiple landscape components, including forest patches in agricultural zones. The implementation of *in situ* conservation outside protected areas is still limited, but it could provide appropriate genetic conservation for many species, with the support of targeted management measures that do not exclude the use of FGR.

As climate change intensifies, active management will be required to maintain the vitality and regeneration capacity of conserved populations. A combination of complementary conservation methods (i.e. *in situ, ex situ* and *circa situm*) may need to be considered and applied simultaneously, tailored to the characteristics of the ecosystems, species and populations of concern. Where tree species diversity is considerable, it may be necessary and most efficient to adopt an ecosystem-based conservation approach. Although individual countries are responsible for conserving their own FGR, international collaboration will become increasingly important to ensure successful *in situ* conservation in the face of climate change and other threats. Interdependence among countries in conserving FGR *in situ* is also likely to increase.

Chapter 7

Ex situ conservation of forest genetic resources

7.1 Introduction

Since SoW-FGR1 was published (FAO, 2014a), there has been an increase in ambition globally to implement forest and broader "treed" landscape restoration. This, in turn, has increased focus on how *ex situ* FGR conservation – in seed gene banks, planted field gene banks (or conservation stands) and other forms – can be integrated into practical tree-planting and management and how it can best support holistic conservation in combination with *in situ* and *circa situm* approaches (Dawson *et al*., 2013). Restoration efforts, as well as broader tree-planting activities, including regular production forestry, require access to high-quality tree seeds and seedlings, supported by *ex situ* germplasm conservation that embraces active seed storage (targeted to more-immediate planting

BOX 6

The bottleneck in providing high-quality tree-planting material for landscape restoration and other tree-planting activities

The lack of access to seeds and seedlings of adequate physiological quality of a diverse range of tree species and the genetic diversity within them, matched appropriately to the planting environment and the needs of planters, is a key barrier to restoration and broader tree-planting success. Trees that get planted are often those for which seeds and seedlings can easily be obtained, irrespective of their suitability for meeting planting goals. Too often, an insufficient diversity of tree species is planted, often only exotics, and the sources of the germplasm used are poorly matched to both the planting environment and the specific requirements of the planters (Jalonen *et al*., 2018). Addressing this major supply bottleneck requires multiple interventions, one of which is to link the *ex situ* conservation of tree genetic resources to practical planting more effectively (Dawson *et al*., 2013).

Sources: **Jalonen, R., Valette, M., Boshier, D., Duminil, J. & Thomas, E.** 2018. Forest and landscape restoration severely constrained by a lack of attention to the quantity and quality of tree seed: insights from a global survey. *Conservation Letters*, 11: e12424. https://doi.org/10.1111/conl.12424; **Dawson, I.K., Guariguata, M.R., Loo, J. *et al.*** 2013. What is the relevance of smallholders' agroforestry systems for conserving tropical tree species and genetic diversity in circa situm, *in situ* and *ex situ* settings? A review. *Biodivers Conserv*, 22:301–324. https://doi.org/10.1007/s10531-012-0429-5 needs) and research into these genetic resources (Box 6; Goodale *et al.,* 2023). Recent global efforts on food production have focused on system diversification, in which fruits, nuts and other tree foods have important roles to play (Ickowitz *et al.,* 2022). The emphasis on food trees requires access to seeds and seedlings of these species in *ex situ* collections in particular, and knowledge about their propagation and management.

As well as supporting the increased use of diverse FGR, *ex situ* conservation has intrinsically become more important since SoW-FGR1 because of the ongoing conversion of forests for agriculture (e.g. Stévart *et al.,* 2019). Threats from anthropogenic climate change that damages forests and woodlands through impacts such as shifts in the range of tree species, the greater prevalence of tree diseases, and heightened fire risk, are also increasingly evident (Alfaro *et al.,* 2014). These drivers are particularly important in regions of high tree endemism, where restricted geographic ranges, specialized habitats and specific ecologies increase conservation threats (Guevara-Andino *et al.*, 2024; Guo *et al.*, 2023). Adequate FGR conservation requires the application of *ex situ* approaches to a broad range of useful tree species and their genetic diversity; it also requires that such approaches are backed by appropriate genetic and phenotypic characterization. A major criticism of tree-seed gene banks has been the weak and broken linkages between conservation and use (Dawson *et al.*, 2013); therefore, to encourage conservation-for-use approaches, work is needed to better link *ex situ* conservation to the tree-seed and -seedling supply systems that provide planting material to growers (Graudal *et al.,* 2021). This is especially important for native tree species, for which seed and seedling sourcing pathways often do not yet exist and for which there has been little characterization of their propagation biologies, including their seed physiologies, or their genetic resources. Even when characterization has been done, the findings may not have been widely disseminated, which limits capacity to act on them.

The Global Plan of Action, which was developed based on SoW-FGR1, called for the further development of efficient *ex situ* conservation systems at the country level (FAO, 2014b). This chapter analyses the progress made in this regard and reviews advances made in *ex situ* conservation approaches, with reference to capacity and technical advances and to the networking and communication between stakeholders needed to make *ex situ* conservation more efficient and effective. The advances made in the last decade have mostly been incremental rather than transformational.

7.2 The state of *ex situ* conservation of forest genetic resources reported by countries

For this assessment, countries were invited to report on whether they had *ex situ* conservation systems for FGR in place and on the area and number of *ex situ* conservation units[14] included in such systems. Countries were also asked to report on the number of *ex situ* accessions[15] by species.

Of the reporting countries, 75 percent (58 countries) indicated they had operational national *ex situ* conservation systems, and ten countries reported that the establishment of such systems had been initiated but were not yet operational (Figure 12; see also the annex). Mexico and Indonesia were the most recent countries to have established operational national *ex situ* conservation systems for FGR (both in 2011); the recent lack of new systems being established globally is indicative of the substantial time and financial investment involved.

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[14] An *ex situ* conservation unit comprises a range of *ex situ* genetic conservation areas of forest trees and other woody plants species (e.g. *ex situ* conservation stands, provenance and progeny trials, and breeding populations).

[15] The term *ex situ* accession commonly refers to samples of FGR stored in a seed bank, a planted field gene bank, or a genotype held in an *in vitro* (clonal) collection.

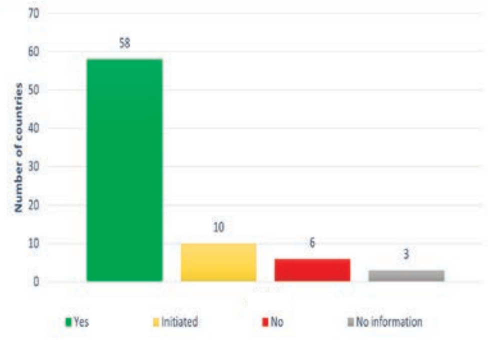
Country reports indicated that, in general, the resources devoted to *ex situ* FGR conservation at the national level have declined due to reduced investments in tree breeding. A notable exception is China, where *ex situ* collections were reported to have increased substantially in the last decade. Investments have also notably been made in *ex situ* FGR collections in the Millennium Seed Bank, an international initiative based at Kew in the United Kingdom of Great Britain and Northern Ireland.

Despite overall limited progress in the number and scale of national *ex situ* FGR conservation programmes in the last decade, several country reports recognized the key role of *ex situ*-conserved FGR for responding to climate change. The reasons given included the importance of conserving resources *ex situ* if they are likely to be lost *in situ* as environmental conditions change; the value of undertaking climate-change-targeted seed-transfer research for adaptation and mitigation strategies based on *ex situ* collections; and the need to support tree species migration and resilient tree-plantings through access to *ex situ* resources.

An important starting point in interpreting information on the nature of *ex situ* collections is understanding how *ex situ* conservation works differently for trees compared with annual crops (Box 7). For trees, there is a much greater focus on "live" *ex situ* conservation stands and other field collections than there would be for annual crops. Thus, although a common component of *ex situ* FGR conservation systems reported by countries was storage facilities for seeds and to a lesser extent for pollen and other tissues (reported by 49 countries), this only marginally surpassed the number of countries reporting *ex situ* conservation stands (48 countries) and field collections (47 countries) (Figure 13). Eight countries reported other components (e.g. arboreta, botanic gardens and DNA banks) in their *ex situ* FGR conservation systems.

FIGURE 12

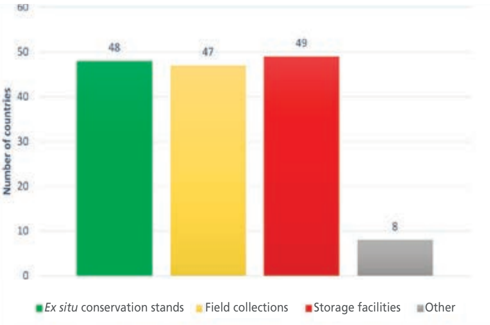
Country responses on whether they have operational national *ex situ* conservation systems



Note: Based on country reports.

FIGURE 13

Components of national *ex situ* conservation systems for reporting countries



Note: Based on country reports.

Seventy-seven reporting countries in the present report indicated they have a total of about 296 000 accessions in seed banks and field collections for tree species. More than 14 500 *ex situ* conservation stands covering about 179 000 ha were reported. Country reports indicated that *ex situ* conservation programmes include 1 077 tree species globally, with the number of species reported highest in Asia (401), followed by Latin America and the Caribbean (293) and North America (202) (Table 12).

In SoW-FGR1, 86 countries had reported 1 800 species under *ex situ* conservation and about 160 000 accessions (FAO, 2014a). The difference in

BOX 7

How *ex situ* conservation differs for trees compared with annual crops

A key difference in *ex situ* conservation between trees and annual crops is the long maturity time for tree species. Thus, the processes of conservation, evaluation, genetic improvement and production of planting material should occur concurrently for trees rather than in sequential steps, as is the case for annual crops (Graudal *et al*., 2021, 2022; Dawson *et al*., 2013). Another differentiating feature is the relatively high proportion of tree species with recalcitrant seeds (that is, the seeds do not remain viable for long, and drying and cooling do not increase seed longevity, as is the case for orthodox seeds). A third distinguishing feature is that, unlike crops, tree seeds have not passed through the typical domestication processes associated with changes in seed-storage behaviour, meaning their behaviour may not be uniform and they may not be amenable to easy storage and germination, even when the seeds are orthodox. A fourth difference is that a substantial proportion of useful tree species are propagated clonally rather than from seed with the aim of maintaining specific trait combinations (this also applies to a smaller proportion of annual crops).

For the above reasons, planted field gene banks – where living trees are conserved, evaluated and used to produce seeds (or clonal materials) for distribution – have an important role in the *ex situ* conservation of FGR, in addition to the role of seed gene banks. Live gene banks also support the adaptation of FGR to changing conditions, as opposed to seed gene banks, which are “frozen” genetically. Ideally, the seed and field gene banks that are established for a tree species are cyclically connected, with field gene banks established from the seed gene banks and the seed produced from field gene banks as they mature used to replenish gene bank stocks (for orthodox-seeded species).

Sources: **Dawson, I.K., Guariguata, M.R., Loo, J., *et al.*** 2013. What is the relevance of smallholders’ agroforestry systems for conserving tropical tree species and genetic diversity in *circa situm*, *in situ* and *ex situ* settings? A review. *Biodivers Conserv*, 22:301–324. https://doi.org/10.1007/s10531-012-0429-5; **Graudal, L., Lillesø, J-P.B., Dawson, I.K., *et al.*** 2021. Tree seed and seedling systems for resilience and productivity. In: The *CGIAR Research Program on Forests T and A (FTA)* (ed) The FTA Highlights of a Decade Series 2011–2021. **Bogor, Indonesia; Graudal, L., Dawson, I.K., Hale, I., *et al.*** 2022. ‘Systems approach’ plant breeding illustrated by trees. *Trends Plant Sci*, 27:158–165. https://doi.org/10.1016/j.tplants.2021.09.009

the number of species is likely due in part to the fewer number of countries that provided data for the present report compared with SoW-FGR1. It is difficult to determine the extent to which the considerably higher number of accessions in the present report reflects an increase in actual *ex situ* efforts and how much is due to better documentation. Countries may have also reported on this metric differently in the two assessments because the reporting guidelines for SoW-FGR1 did not provide a definition of accession.

The number of species reported to be under *ex situ* conservation in the present report is about 2 percent of all tree species, suggesting

TABLE 12
Number of species included in *ex situ* conservation programmes, by region

Region	Number of species*
Africa	140
Asia	401
Europe	167
Latin America and the Caribbean	293
Near East	1
North America	202
Southwest Pacific	52

Notes: * The total number of species reported by region sums to more than the 1 077 identified in *ex situ* conservation programmes globally because a substantial number of species are included in programmes in more than one region. Based on country reports.

that countries focused their FGR reporting on species that are important for forestry (including agroforestry) and have known or potential uses. BGCI (2024) estimated that 30 percent of the world's tree species (regardless of their utility) are present in botanic gardens, arboreta and other *ex situ* collections. This difference is explained partly by the focus of botanic gardens on conserving species rather than the genetic diversity within species and on safeguarding rare and endangered species that often have no well-recognized forestry uses. Another reason for the difference is that the estimate by BGCI covers almost all the world's countries and territories (compared with 77 countries that provided reports for the present report).

7.3 Advances in *ex situ* conservation methods

Seed gene banking

Seed gene banking, in which dried seeds are stored in sealed containers under cold conditions, is practised widely for trees with orthodox seeds that can withstand drying and cooling. In this way, many species and a representative sample of their genetic diversity – if range-wide collection has been undertaken – can be stored relatively inexpensively and in a concentrated space, making the approach economically and practically viable (Pritchard *et al.,* 2014). During drying, the seeds enter a quiescent stage in which metabolic processes are reduced almost to a stand-still; continuing in this state, low relative humidity and temperatures delay the process of physiological aging. Orthodox tree seeds can be stored successfully for a few years (typically 3–5 years) at 3–7 percent moisture content and 5 °C, whereas this is possible for 20 or more years at minus 20 °C (De Vitis *et al.,* 2020).

International initiatives are seeking to boost *ex situ* tree-seed collections. Foremost among these is the Global Tree Seed Bank Programme (GTSBP) in the United Kingdom of Great Britain and Northern Ireland, which started in 2014 with the establishment of the Global Tree Seed Bank at the Millennium Seed Bank, West Sussex, where around 11 000 tree and shrub species were already conserved. The Millennium Seed Bank worked with partner organizations around the world from 2015 to 2019 to collect more than 3 800 tree and shrub species, emphasizing rare, threatened and useful trees and filling gaps in knowledge to underpin their effective conservation. The GTSBP is continuing in a third phase, with a focus on improving the preservation of difficult-to-store tree seeds and on training in seed conservation in Africa, Asia and Latin America.

The ICRAF[16] agroforestry tree gene bank became part of the CGIAR[17] gene-bank platform in 2012; since then, it has been monitored using globally developed gene-banking indicators. This gene bank, located in Nairobi, Kenya, conserves about 7 000 accessions for 195 species. It also holds almost 16 000 accessions of 67 tree species in 37 field gene banks in 17 countries.

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[16] Known as ICRAF in 2012; now known as CIFOR-ICRAF.

[17] Formerly known as the Consultative Group for International Agricultural Research.

Seeds of pod mahogany (*Afzelia quanzensis*) analysed for *ex situ* conservation in the United Republic of Tanzania

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Despite the general expansion of the internet as a source of information in the last decade, the availability of systematic knowledge on tree species stored in seed collections globally, including active seed collections, has declined since SoW-FGR1. In the past, the managers of active tree-seed collections would provide printed catalogues of their seed stocks (in the case of commercial suppliers, of seed for sale), which allowed the cross-tabulation of holdings. On this basis, ICRAF produced the Tree Seed Suppliers Directory in 1997, having gathered information from 144 tree germplasm holders and providers, listing a total of 5 874 woody perennial taxa (Kindt *et al.,* 2002). The Directory is no longer printed but is still available online (ICRAF, undated). An attempt to update it was made in 2015, but it proved impossible to obtain the necessary level of detail on seed stocks from commercial tree seed suppliers, who appear now to rely on online postings of their individual catalogues, and there was no simple way of scraping data from these information sources. This leaves a significant gap in knowledge on which tree seeds are in storage and are actively available to planters globally, with those planters (and researchers) seeking seed generally making their own *ad hoc* inquiries.

Progress in predicting tree-seed storage behaviour. The storage behaviour of seeds is best known for temperate and boreal tree species, which are relatively few in number compared with the much wider range of tropical trees (Wyse and Dickie, 2017; Wyse, Dickie and Willis*,* 2018). Research coverage of tropical trees is increasing incrementally, as discussed below.

The Ellis and Roberts (1980) equation, which provides a basis for predicting seed longevity under storage conditions for orthodox plant seeds, has been used widely to derive seed viability constants and standards (e.g. Dickie and Bowyer, 1985; Dickie *et al.,* 1990; Fantinatti and Usberti, 2007). The equation continues to be used for tree seeds and is an important starting point for modelling longevity where research on all the species that need to enter storage is impractical. Moreover, discrepancies between predictions and actual storage performance indicate those areas where further research is needed (Solberg *et al.*, 2020).

Recent research on the seed-storage behaviour of trees has supported mostly incremental progression in knowledge, building on past achievements that were reviewed by Pritchard *et al.* (2014). New knowledge supports the further parameterization of models and provides specific information on tested species that support conservation. For example, studies of the seed viability of six European trees (*Malus sylvestris*, *Pyrus communis*, *Sorbus aucuparia*, *Prunus avium*, *Prunus padus* and *Cornus sanguinea*) concluded that the species with deeper physiological dormancy (*S. aucuparia*, *P. padus* and *C. sanguinea*) tended to be more tolerant of desiccation and low temperatures (Wawrzyniak *et al.,* 2020). In another example based on the study of five tropical forest tree species (*Chamaedorea glaucifolia*, *Cymbopetalum baillonii*, *Magnolia mexicana*, *Nectandra coriacea* and *Ternstroemia tepezapote*) in southeastern Mexico, Becerra-Vázquez *et al.* (2018) reported that seed longevity was related to various functional and ecological traits, along with prevailing weather conditions at the time of seed dispersal. Accelerated-ageing tests mimicking the ageing process of seeds under storage conditions were conducted on seeds of 22 native woody species found in the United Kingdom of Great Britain and Northern Ireland by exposing them to higher temperatures and relative humidities than the standard storage conditions (Davies *et al*., 2020). This study indicated that seed-storage behaviour generally follows a phylogenetic kinship pattern across related taxa, but caution is needed in making broad as well as specific conclusions on the potential seed-storage life at the species, genus and family levels.

Associations between desiccation tolerance and habitat, agroecological zones, phylogeny and seed traits (e.g. Ellis *et al.,* 2007; Hamilton *et al.,* 2013; Pritchard *et al.,* 2014; Obroucheva *et al.,* 2016; Wyse and Dickie, 2017), among other factors, have been used to develop advanced mathematical models for predicting seed-storage behaviour. One of the first multivariable probabilistic prediction models applied measures of seed mass, moisture content, seed coat ratio and rainfall in the month of seed dispersal to 104 species in 37 families in a semi-deciduous tropical forest in Panama (Daws *et al.,* 2006). A binary logistic regression predicted desiccation intolerance for seeds with large mass and thin seed coats with reasonable accuracy. The model was also used to successfully predict seed desiccation tolerance of woody species in the Xishuangbanna tropical rainforest in Yunnan Province in southern China (Lan *et al.,* 2014).

Wyse and Dickie (2017) studied information available in Kew's Seed Information Database (Royal Botanical Gardens, 2022) for 17 378 plant taxa, of which 643 were considered desiccation-sensitive and 16 605 were thought to be desiccation-tolerant. Wyse and Dickie (2017) built independent prediction models based on taxonomic relatedness and habitat distribution and found that taxonomic prediction worked well for lower levels of taxonomic relationships but showed greater discrepancy at higher taxonomic levels. The habitat-based prediction model developed by Wyse and Dickie (2017) was also useful for predicting the seed desiccation response.

Using taxonomic affinity, habitat and seed-mass information for 17 539 plant species, Wyse and Dickie (2018) further fitted regression models to predict seed desiccation response, with more or less similar outcomes to their earlier work. The most important predictor variables were the seed desiccation responses of a species' relatives, seed mass, and annual precipitation. Almost all the annual herbaceous species studied were found to be desiccation-tolerant, whereas a substantial proportion of perennial herbaceous species were desiccation-sensitive, with a particularly high prevalence of this among tropical evergreen non-pioneer rainforest trees (see also Tweddle *et al.,* 2003; Kettle, 2012; Umarani *et al.,* 2015).

Although not yet tested on tree species, Nehoshtan *et al*. (2021) proposed a model that uses deep learning (high-end artificial neural network analytics) and red-green-blue imaging technology to predict the germination responses of commercial vegetable species' seedlots. The study, involving training seedlots of known outcome and test seedlots for assessing the predictive outcome, resulted in an approach suitable for industrial seedlot sorting. Such new computational methods based on machine learning could be useful for predicting the germination responses of tree seeds, but they require testing. The ease of the red-green-blue imaging approach, and its cross-species application, adaptive learning capacity, and potential for upscaling, support such testing.

Further understanding desiccation intolerance as a key issue in seed conservation. Sensitivity to seed desiccation, influenced by factors such as seed oil content, endosperm quality and the amount of storage tissue, is a prime concern for storing tree seeds. According to Umarani *et al.* (2015), the vast majority of tree species belonging to family Dipterocarpaceae have recalcitrant seeds, but the proportion is less than 10 percent for Malvaceae, Rubiaceae and Bignoniaceae.

Kew's Seed Information Database (Royal Botanical Gardens, 2022), first released in 2001, is a primary source of data on seed-desiccation sensitivity (e.g. it was used by Umarani *et al.*, 2015), but it is heavily biased towards desiccation-tolerant (and temperate) plants (Wyse and Dickie, 2017). In the last decade, studies that have helped redress this situation for tree species include those of Lima *et al.* (2014) (for the Amazon), Waiboonya *et al.* (2019) (for northern Thailand) and Mattana *et al.* (2020) (for the Caribbean). These authors compared experimental findings with predictive models and found good overall consistency, although the findings should be treated with caution given the biased representation in the databases, varied correlations for the same variables in different studies, and confounding factors, including habitat and taxonomic relatedness.

Although the physiology of recalcitrance is understudied, three potential biological reasons for reductions in seed viability have been further elucidated in recent years. One of these is cellular mechanical damage due to the vacuolar collapse of cellular organelles during drying: the embryos of recalcitrant seeds have a large proportion of vacuoles in their cells, and a positive correlation has been observed between vacuolation and recalcitrance (Farrant *et al.,* 1992; 1997).

Increasingly, advanced genomic approaches provide opportunities to understand the genetic and molecular basis of seed storage behaviour. A study examining 86 reports of diverse annual plants summarized the roles of multiple quantitative trait loci (QTLs) and genes (transcription factors, hormonal and signalling pathway components, and seed storage proteins) involved in seed ageing processes (Arif *et al.,* 2022). A recent differential gene expression study of Chinese cork oak (*Quercus variabilis*) found that more than 4 000 genes were significantly affected by seed desiccation over a period of 15 days (Li *et al.,* 2021). Those affected were primarily the heat-shock family proteins, late embryonic abundant proteins, plant hormone signal transduction pathways, and glycerophospholipid metabolism genes. Such genomics studies could help the development of tools and models for predicting tree-seed desiccation tolerance and in devising seed treatments to enhance low water tolerance.

High-throughput proteomics have been used to functionally understand tree-seed desiccation behaviour. In a study of holm oak (*Quercus ilex*), Sghaier-Hammami *et al.* (2015) compared the protein profiles of different embryonic regions and found a high level of protein compartmentalization in different parts of the embryo. Among 226 differentiated proteins, the embryonic axis had significantly higher amounts and a more diverse set of proteins compared with cotyledons and the tegmen. The tegmen had high representation of stress- and defence-related proteins, albeit far less than the embryo axis. Another proteomic analysis of germinating embryos in the same oak species revealed 153 differentially expressed proteins (Romero-Rodríguez *et al.,* 2019).

Although genomic, proteomic and other advanced studies to date do not provide anywhere near a full picture of the mechanisms of desiccation intolerance in tree seeds, they do open up new avenues for looking at this poorly understood and scarcely studied phenomenon, with combinatorial transcriptomic and systems biology approaches. Findings from model plants and annual crops could, in principle, be helpful for understanding the phenomenon in tree species and could have important applications in FGR conservation. For example, the results could support the augmentation of seed longevity by external chemical applications or physical treatments and could also be used to optimize basic storage conditions. Confirmatory studies in trees are required, however, to support application.

Field gene-banking

Planted field gene banks and conservation stands have important roles to play in the *ex situ* conservation of tree species, especially those that produce recalcitrant seeds or are propagated vegetatively to maintain true-to-type lines, for which conventional seed storage approaches are inappropriate (Pence *et al*., 2022). Many threatened tree species are recalcitrant, and establishing planted field gene banks of these species remains a priority (Wyse, Dickie and Willis, 2018). Field gene banks also have a crucial role to play in delivering the seeds of high-demand orthodox-seeded trees (Graudal *et al.,* 2021). With recent conceptual advances in holistic systems approaches to tree breeding, such as tree diversity breeding, as described by Graudal *et al.* (2022), field gene banks that also evaluate tree germplasm have new and specific roles to play (Hendre *et al.,* 2022). Box 8 explores the concept of tree diversity breeding and some of its implications for tree field gene-banking.

Botanic gardens hold most live planted *ex situ* tree conservation collections of trees. BGCI maintains a database of botanical institutes that includes about 800 well-established botanic gardens that collectively are estimated to harbour 60 000–80 000 plant species, of which 6 881 are trees (these are held as seeds as well as live plants; O'Donnell and Sharrock, 2017). A substantial proportion of these tree species are single-country endemics, emphasising their vulnerability and urgent need for conservation. The finite space and resources of botanic gardens, however, limits the number of trees of a given source that can be planted, narrowing genetic diversity and reducing their ability to produce healthy progeny. The possibility of vegetative regeneration of some live tree collections is an option for maintaining existing diversity.

CIFOR–ICRAF and partners maintain a network of field gene banks of agroforestry tree species that emphasizes the adequate representation of intraspecific diversity. These field collections have grown in coverage in the last decade: for example, the number of accessions in field gene banks grew from 3 600 on 26 sites in 2013 to almost 16 000 on 37 sites in 17 countries in 2023 (as indicated above).

Another ongoing major issue for botanic gardens is that they tend to suffer from the absence of plausible routes by which the genetic resources they conserve – whether as seeds or live collections – can be repatriated to support biodiversity in forests and woodlands, including agroforestry systems (Dawson *et al.,* 2013). This does not negate their value for *ex situ* conservation *per se*, but it often means that their utility lies more in the characterization of tree species' biology, training, and raising public awareness than in supporting the practice of reforestation and restoration. Cavender *et al.* (2015) assessed the challenges facing botanic gardens in conserving trees and promoting their use and made recommendations for improving the situation, including greater networking to improve coordination between gardens and support pathways to germplasm use. A global partnership platform called ArbNet spearheaded by The Morton Arboretum was established in 2011 to strengthen arboreta by setting standards, identifying capacity gaps and strengthening the global community of tree-focused organizations. ArbNet and BGCI joined forces in 2017 to fund international collaboration between tree-focused botanic gardens and arboreta for the purpose of exchanging skills, resources and expertise to advance tree conservation efforts and support germplasm use.

Turner-Skoff *et al.* (2022) discussed the important role of ArbNet in supporting conservation and generating opportunities to advance the science and conservation of trees.

They also indicated opportunities for growth in the platform's next decade, including greater emphasis on supporting arboreta in biodiversity hotspots, more work with under-resourced communities, giving greater consideration to urban tree-planting, and being more closely connected with on-the-ground conservation and restoration projects.

There has been renewed interest in the use of breeding seedling orchards (BSOs; described by Barnes, 1995) as an approach for linking the conservation of tree genetic resources with use. BSOs conserve trees, enable the evaluation of genetic variation, and supply tree-planting materials in the context of integrated tree-seed and -seedling systems. They are being established to help meet seed demand for large-scale tree-planting initiatives (Graudal *et al.,* 2021). The Provision of Adequate Tree Seed Portfolios project (PATSPO) in Ethiopia is a recent example (see also Box 9 in Chapter 8), with 55 BSOs established to January 2025. PATSPO is designed to support Ethiopia's massive landscape restoration target of 15 million ha by 2030. Under it, BSOs have been established for 22 tree species, including various acacias and eucalypts, as well as *Afrocarpus falcatus*, *Albizia gummifera*, *Azadirachta indica*, *Cordia africana*, *Cupressus lusitanica*, *Faidherbia albida*, *Grevillea robusta*, *Hagenia abyssinica*, *Juniperus procera*, *Millettia ferruginea*, *Moringa stenopetala*, *Olea europaea*, *Pinus patula* and *Prunus africana*, representing species introduced and native to Ethiopia in about equal numbers. The same model of BSO establishment is being applied in other new tree-planting projects in Africa, such as the Transforming Eastern Province through Adaptation project in Rwanda and the Right Tree in the Right Place – Seed project in Burkina Faso, Ethiopia, Kenya, Rwanda and Uganda.

A key challenge of PATSPO and similar initiatives is to scale up and scale out lessons about tree-seed and -seedling supply to other locations and species. This is especially so for native tree species, which have become the focus of much tree-planting in the last decade but have received limited attention to date in the setting up of seed and seedling delivery.

To scale up BSOs it is also necessary to understand the challenges and trade-offs involved in managing them for both conservation and genetic improvement. Innovations that combine ecological genomics[18] and genome-based field selection[19] can be helpful for maintaining a balance between conservation and production functions (Funda and El-Kassaby, 2012; Chaloupková and Lstibůrek, 2022; Ousmael *et al.*, 2024).

Several countries have set up genetic improvement programmes for native and introduced tree species as part of their *ex situ* conservation efforts. In Argentina, tree improvement programmes include genetic trials of provenances and progenies for a range of species. The Instituto Nacional de Tecnología Agropecuaria Genetic Resources Network funds activities to maintain field trials and collections for conserving *ex situ* and *in vivo* both native (e.g. *Araucaria*, *Austrocedrus*, *Cedrela*, *Neltuma* and *Nothofagus* spp.) and introduced (*Eucalyptus*, *Pinus*, *Populus* and *Salix* spp.) species in these genera.

Other methods of *ex situ* conservation

Cryopreservation is a technique that conserves vegetal structures at very low temperatures, such as in liquid nitrogen (at minus 196° C), at which cellular and physiological processes are arrested. The plant material is processed in cryogenic material before storage to prevent tissue damage, and pollen, seeds, shoot tips, dormant buds, cell suspensions, embryonic cultures, somatic and zygotic embryos, and callus tissues, can all be stored. It can be used to conserve recalcitrant tree species, but the work done to date on cryopreservation has concentrated on

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[18] Ecological genomics is the use of genomics to understand natural variation in relation to environmental variables and the adaptive performance of trees (e.g. Hung *et al., 2013).*

[19] Genome-based field selection involves the use of genomics to associate and estimate traits of importance in experimental trials.

BOX 8

Tree diversity breeding and its implications for tree field gene-bank design

Trees provide an excellent example of where a systems approach to breeding is important for addressing global challenges effectively. Graudal *et al.* (2022) labelled building links between tree-breeding methods that are responsive to global trends and challenges as "tree diversity breeding", which they explored by considering pairwise combinations of four global trends related to participation, environment, biotechnology and markets. This gave rise to six suggestions for action: (1) the use of citizen science tree-breeding approaches (thus bridging trends in participation and environment); (2) new statistical approaches to support progress in the understanding of tree genetic adaptation (environment and biotechnology); (3) the manipulation of tree product quality/processability-related genes (biotechnology and markets); (4) making use of advances in production system modelling of tree varieties (markets and participation); (5) the manipulation of tree architecture-related genes and other genes that determine the labour costs of tree production (participation and biotechnology); and (6) the use of novel methods to explore genetic, tree-product quality, and production system design relationships (environment and markets).

Hendre *et al.* (2022) conceptually explored the implications of tree diversity breeding for organizations that engage in *ex situ* tree gene-banking and showed how its adoption could affect the design and operation of tree field gene banks that are also used to support tree selection and breeding in two ways. First, the evaluation of field gene banks will likely need to give increased importance to traits that support the provision of ecosystem services, future and current climate adaptation, product quality, and the labour costs of tree production. More attention will need to be given, for example, to evaluating tree architecture and flowering phenology because these traits determine the capacity of a tree to provide ecosystem services such as habitat for other forest organisms. Second, the design of field gene-bank stands will likely need to support more holistic, systems-based evaluation, which may require establishing multispecies stands (rather than single-species stands). Multispecies stands enable explorations of the interactions among tree species and between trees and annual crops and support the role of genetics in defining new, integrated production systems. Hendre *et al.* (2022) noted that, given the correct design and implementation of mixed-species gene-bank stands, it should be possible for these stands to retain important roles in propagule supply.

Sources: **Graudal, L., Dawson, I.K., Hale, I., *et al.*** 2022. 'Systems approach' plant breeding illustrated by trees. *Trends Plant Sci*, 27:158–165. https://doi.org/10.1016/j.tplants.2021.09.009; **Hendre, P.S., Graudal, L., Kindt, R., Hale, I., Powell, W., Jamnadass, R., Thomson, L. and Dawson, I.K.** 2022. *Operationalizing an innovative systems approach for breeding agroforestry trees.* CIFOR–ICRAF Infobrief No. 378. Nairobi, World Agroforestry. https://doi.org/10.17528/cifor/008758 commodity tree crops and there is a need to better understand its role and efficacy for forest tree species. For avocado (*Persea americana*), various plant materials, such as somatic embryos and shoot tips, have been preserved successfully, and methods have recently been further improved (O'Brien *et al.,* 2021). In coffee (*Coffea arabica*), progress has been made in preserving zygotic embryos using droplet-vitrification and encapsulation–vitrification protocols without dehydration (Valdés *et al.*, 2021).

Volk *et al.* (2017) reported on the cryopreservation of shoot tips of 32 citrus taxa, where the tips were preserved and revived with varying degrees of success. Examples of other studies in the last decade include the cryopreservation of somatic embryos of cocoa (*Theobroma cacao*) (Adu-Gyamfi *et al*., 2016; 2020) and holm oak (Barra-Jiménez *et al*., 2015). Successful revival was achieved in both cases. Ballesteros and Pritchard (2020) noted that establishing an integrated platform for the *ex situ* conservation of oak species by cryobiotechnology is now possible and that initial efforts could focus on centres of species diversity of the genus. Cryopreservation of embryo axes is the best method to date for preserving recalcitrant tree seeds (Berjak and Pammenter, 2017), but it is costly and technologically demanding (Engelmann, 2012; Benelli *et al*., 2013), as well as experimentally challenging.

In vitro conservation embraces tissue-culture methods in which a plant is stored and maintained under artificial conditions of temperature, nutrition and water. The possible conditions include those conducive for normal growth, slow growth and arrested growth, and the methods could involve other modifications of plant tissues and organ cultures. Many commercially important temperate fruit trees and nuts, such as those belonging to the genera *Malus*, *Morus*, *Prunus*, *Punica* and *Pyrus,* have been conserved using *in vitro* techniques such as slow culture, cell culture, shoot culture and shoot tip culture, with varying success rates, as reported recently by Reed (2020). Hassan (2017) used growth-retardant media to successfully store date palm somatic embryos under slow-growth conditions. Arbeloa *et al.* (2015) successfully developed or stored slow-growth cultures for *Crataegus*, *Cydonia*, *Eriobotrya Ficus*, *Malus*, *Punica*, *Prunus* and *Pyrus* species.

Although the protocols for *in vitro* propagation were also available more than a decade ago for many tree species in genera such as *Azadirachta*, *Cariniana*, *Cedrela*, *Dalbergia*, *Diospyros*, *Garcinia*, *Lagerstroemia*, *Melia*, *Ricinodendron*, *Santalum*, *Sapium*, *Swietenia* and *Tabebuia* (Pijut *et al*., 2012), their application for conservation does not seem to have accelerated markedly, with some exceptions (Hernández-García *et al*., 2021; Juan-Vicedo *et al.* 2022; Mudio *et al*., 2023). Application to the conservation of non-fruit-tree species has particularly lagged. One reason could be poor transferability of *in vitro* propagation protocols between ecotypes and individuals. Moreover, many perennial species produce phenolic compounds that hamper growth and rooting in *in vitro* conditions (Aliyu, 2005; Jones and Saxena, 2013; Kanjana *et al*., 2024).

Tree DNA banking can tangentially be considered as a method of germplasm conservation. Indirectly, information extracted through DNA sequencing can be used for conservation purposes by understanding the prevalence of rare alleles, studying allelic and population movements, and helping build genetic and genealogical relational phylogenies, among other applications. In addition, gene editing methods have made significant advances in recent years, meaning information extracted from specific DNA sequences could be applied to directly recreate lost or rare allelic combinations of importance (Bewg *et al.,* 2018). The long-term maintenance of DNA requires special storage provisions to maintain integrity and standard arrangements for access. The global Genesys plant genetic resources platform contains 648 records of FGR stored in DNA banks for 33 species, as of November 2023.

7.4 Conclusions

SoW-FGR1 found that the *ex situ* conservation of FGR was confined primarily to economically important species and to endangered or threatened species (FAO, 2014a). The present report confirms that this situation still prevails. The Global Plan of Action called for the establishment and development of efficient and sustainable *ex situ* conservation programmes, including *in vivo* collections and gene banks (FAO, 2014b). It also stressed the importance of documenting FGR and promoting research on seed biology and conservation methods and improving human and institutional capacity for *ex situ* conservation.

Progress has been only incremental in the *ex situ* conservation of FGR since SoW-FGR1, despite increasing global demand for tree germplasm (see also Chapter 8). This applies to the development of national *ex situ* conservation programmes and to technical developments in conservation methods, as well as to documentation efforts to increase data availability. For example, much work remains to be done to define the technical requirements of seed storage for a broad range of tree species. Incremental progress includes modelling the storage characteristics of a more diverse set of tree species, and transformational potential for deeper insights exists through advances in transcriptomic, proteomic and related approaches. Much research is needed on the use of *ex situ* collections to advance knowledge on tree–site matching in the context of climate change, especially through studies of genotype-by-environment interactions. To justify investments in the *ex situ* conservation of FGR, these efforts and related research need to be connected to the socioeconomic contexts of users and societies.

Further actions are needed to fully integrate the *ex situ* conservation of FGR with practical tree-planting, especially for the conservation and use of native tree species. Models of action have been developed in the last decade to support this, including the use of appropriately managed BSOs that can simultaneously fulfil conservation, characterization and planting-material supply functions, albeit with trade-offs that are not always well understood. These models need to be scaled up and out.

Innovative approaches are needed to support conservation with growers – ranging on the spectrum between *ex situ* and *circa situm* conservation. For example, they could involve the use of smartphone-based digital apps that allow farmers who have planted or manage trees of conservation value on their land to receive digital credit payments for tree maintenance by

Part 4

STATE OF USE, DEVELOPMENT AND MANAGEMENT OF FOREST GENETIC RESOURCES

Chapter 8

State of the use of forest genetic resources

8.1 Introduction

The use of FGR, such as in sustainable forest management, makes an important contribution to sustainable development, and many countries consider such use to be the ultimate reason for conserving FGR (FAO, 2014a). The production, distribution and deployment of germplasm and planting material are crucial for afforestation, reforestation, forest restoration and other tree-planting efforts, improving livelihoods, and tackling biodiversity loss, climate change and desertification. This chapter focuses on the use of FGR for establishing new forests and tree-based production systems; Chapter 9 addresses FGR use in the context of tree improvement and breeding; and Chapter 10 examines the management of existing forests.

Seed is the most common form of tree germplasm used for raising planting stock, but other plant parts (e.g. cuttings, buds, scions, explants and embryos) are also used for this purpose. The term “forest reproductive material” encompasses seeds and other plant parts, as well as plants raised by means of these parts (OECD, 2023), and wildlings (seedlings resulting from natural regeneration and gathered in forests).

The production of forest reproductive material offers limited economic rewards for the private sector (given the long timeframes involved); markets for forest reproductive material are poorly developed in many countries (FAO, 2014a); and natural regeneration is still the predominant method for regenerating the world’s forests. For these reasons, countries often consider the production of forest reproductive material as a basic but strategic activity necessitating public-sector involvement and oversight. National tree-seed centres, often run by forest services or forest research institutes, are typically the main public agencies tasked with the collection, storage and distribution of forest reproductive material, and they also supply it to the private sector. Additionally, countries may have designated governmental agencies overseeing the production of forest reproductive material and certifying its quality for domestic and international markets. Private-sector actors, such as forestry companies and community enterprises, also produce this material, but they generally use a large part of their production for themselves (FAO, 2014a). SoW-FGR1 found that informal-sector players, such as smallholder farmers and forest-adjacent communities, play important roles in sourcing tree germplasm and propagating planting stock for their own use or for local markets. Seeds collected by such players often do not meet the requirements for national or international certification, however, and the material tends to have less genetic diversity than that produced in the formal sector (FAO, 2014a).

Historically, FGR have been transferred extensively and used for different purposes within and beyond species’ natural ranges (Koskela *et al.*, 2014). The geographical origin of seed sources has a major influence on the growth and performance of planted trees (see König, 2005). Since the early nineteenth century, the guiding forestry principle for using tree species and their provenances has been the matching of climatic

Cleaning of umbrella thorn (*Vachellia tortilis*) seeds in the United Republic of Tanzania


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and other environmental conditions between a seed source and the deployment site. Climate change is increasingly posing challenges to this principle, however, because climatic conditions are a moving target and there is considerable uncertainty in both the short and long terms (e.g. Harris *et al*., 2006; Xu and Prescott, 2024).

The Global Plan of Action called for the reinforcement of national tree-seed programmes to ensure the availability of high-quality germplasm for tree-planting (FAO, 2014b). It also stressed the importance of promoting restoration and rehabilitation using genetically appropriate material and supporting climate-change adaptation and mitigation through the proper management and use of FGR. This chapter summarizes the information reported by countries on their tree-seed programmes for the production of forest reproductive material and trends in demand and supply. It also discusses the implications of climate change for FGR use, summarizes selected research findings on this topic, and presents the needs, challenges and opportunities reported by countries.

8.2 Production and certification of forest reproductive material

Genetically, forest reproductive material can be either improved or unimproved, and its intraspecific diversity can range from a single genotype (clone) to a large amount of a species' genetic diversity. Unimproved germplasm is commonly used in forestry for propagating planting material (or for direct sowing) – genetically improved germplasm is typically available for relatively few commercially important species (FAO, 2014a). Even in the case of commercially important species, many countries rely on both improved and unimproved germplasm because there is considerable annual variation in seed production in forest trees for various biological reasons (e.g. mast seed years) and because of the long lag before newly established seed orchards start producing improved germplasm.

In addition to the collection of seeds and wildings, forest reproductive material is produced vegetatively. This approach allows the large-scale production of preferred genotypes in a short period and is also useful for producing planting stock for species with recalcitrant seeds (FAO, 2011). Macropropagation using cuttings has a long tradition in forestry, but micropropagation techniques are also increasingly applied despite their higher costs and more sophisticated technical requirements (FAO, 2014a). The most effective micropropagation techniques for forest trees are organogenesis using shoot tips and buds and somatic embryogenesis in which embryos are developed asexually from plant tissue in *in vitro* conditions (Wilhelm, 2005). Because the production of forest reproductive material involves the storage of seeds, clone collections and tissues for micropropagation, it also contributes to the *ex situ* conservation of FGR.

The country reports confirmed that, globally, the use of unimproved germplasm continues to play a major role in the production of planting stock. The availability of improved germplasm varies considerably between countries. In Spain, more than 95 percent of all the forest reproductive material used is unimproved, but it is collected from identified seed sources. In Sweden, in contrast, 97 percent of the seedlings planted in 2019 were raised from improved germplasm. In Sweden, which has advanced tree-breeding programmes, nearly all reforestation involves only two species, Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). The share of improved germplasm is lower in most other countries: about 30 percent of harvested seed is improved in the Republic of Korea, and the share of improved seeds for the main forestry species in Ukraine ranges from 20 percent to 40 percent. The availability of improved germplasm also varies between species within countries, depending on the progress made in tree breeding and other circumstances. In Norway, more than 90 percent of Norway spruce seeds sold in 2018 was improved, but most of the Scots pine seeds were unimproved, reflecting the strong focus on Norway spruce breeding there. The United States of America reported that unimproved seed is used primarily in the northeastern states and Great Lakes region and improved seed is used mostly in the western and southeastern states.

The certification of forest reproductive material to provide reliable information on the quality and origin of germplasm is essential for the domestic and international trade of forest tree seeds, as well as for use in nurseries and the field. Since the late 1960s, two certification schemes have facilitated the international trade of forest reproductive material: the Forest Seed and Plant Scheme of the Organisation for Economic Co-operation and Development (OECD), and the European Union's scheme for the marketing of forest reproductive material, re-established by Council Directive 1999/105/EC. The two schemes, which are mutually compatible, divide basic material (i.e. sources from which the reproductive material is obtained) into four categories (see also Table 13): (1) source-identified; (2) selected (at the population level); (3) qualified (selected at the individual level); and (4) tested. Source-identified and selected materials require that the geographical coordinates of the collection site are recorded and that effective population size is large enough to maintain genetic diversity.

Thirty countries in Africa, Europe and North America are participating in the OECD scheme, which is open to all member countries of the United Nations and the World Trade Organization. Each participating country must designate an authority to oversee the scheme's implementation. The designated authority maintains a national register in which each collected or produced unit of approved basic material (e.g. seedlot) is recorded, and it issues certificates for forest reproductive material. All professional operators involved in the collection, production, storage and processing of forest reproductive material, as well as in its international trade, must also be registered with the designated authority. More than 400 tree species are eligible for certification, and the website of the OECD scheme provides annual statistics of the material produced and traded internationally.

TABLE 13
Various types of basic material and how they can be certified under the Organisation for Economic Co-operation and Development's Forest Seed and Plant Scheme

Basic material	Categories of forest reproductive material			
	Source-identified	Selected	Qualified	Tested
Seed source	X			
Seed stand	X	X		X
Seed orchard			X	X
Parents of family/families			X	X
Clone			X	X
Clonal mixture			X	X

Source: Organisation for Economic Co-operation and Development (OECD). 2023. *Rules and regulations: OECD Forest Seed and Plant Scheme*. Paris. Avalable at: https://www.oecd.org/content/dam/oecd/en/topics/policy-sub-issues/forest-seed-and-plant/2022%20oecd-forests-scheme-brochure.pdf

The European Union scheme operates in the same way but is only open to European Union member countries. All approved basic material is documented in national registers and the FOREMATIS database. Several countries that have entered negotiation processes to join the European Union have also implemented Council Directive 1999/105/EC in their national legislations. The overlap between the OECD and European Union schemes in terms of participating countries is considerable because most European Union members have also joined the OECD Scheme, which allows them to certify material for international trade beyond the European Union common market.

Several other countries have designed their national certification systems to follow either the OECD or European Union scheme but have not joined these schemes officially. Argentina reported that its certification system for forest reproductive material is based on the OECD scheme and is overseen by the National Seed Institute – a government agency under the Ministry of Agriculture, Livestock and Fisheries – as the designated authority. Ukraine reported that it drafted a law on forest reproductive material in 2019 based on Council Directive 1999/105/EC and another law in 2020 for updating the forest seed and nursery system, although these draft laws have not been approved. Sri Lanka indicated that it lacked a certification system for reproductive material obtained from natural forests, although the Research Institute in the Department of Forest Conservation provides national-level certification for improved seed produced in seed orchards.

These certification schemes do not provide guidelines for the deployment of forest reproductive material. Based on the information that accompanies the traded material, however, buyers can make informed decisions on where to use the material following national guidelines and rules established for this purpose. Some countries use legislation to promote the use of certified material. For example, a law in Argentina established a framework of economic incentives to promote reforestation and sustainable forest management. A key aspect of this law is the additional support (in the form of a 10 percent increase in subsidies) offered when forests are established using certified seeds.

8.3 State of national tree-seed programmes

For the present assessment, countries were invited to report on the existence of national or subnational tree-seed programmes and the species included, as well as on extension efforts promoting the appropriate use of FGR. They were also invited to report on the number and area of seed stands and seed orchards, by species, and the amount of planting stock produced through macro- and micropropagation, by species.

National (or subnational) tree-seed programmes are mechanisms for overseeing and coordinating the selection, procurement, documentation, storage and testing of forest reproductive material. They typically bring together an official body responsible for approving basic material and maintaining a national (or subnational) register of this material and (public and private) stakeholders involved in its production and use.

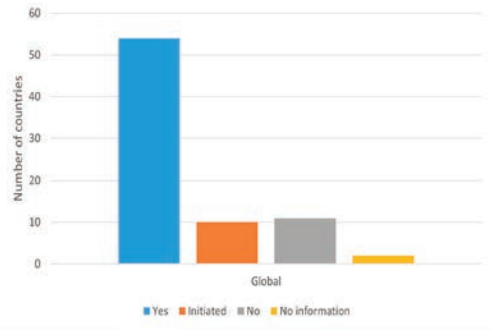
Of the 77 reporting countries, 70 percent (54) indicated that they have national tree-seed programmes (Figure 14; see also the annex). Most of these programmes have been in place for a long time; the first, in Norway, was established in 1895, and many others originated in the 1950s and 1960s. Two countries, Fiji and India, created their national tree-seed programmes in the last decade.

Countries might also produce large amounts of forest reproductive material without national-level structures. For example, rather than a single national programme, the United States of America has more than 100 tree-breeding and -seed programmes in individual states. The USDA Forest Service runs the National Seed Laboratory, which provides scientific and technical support to the various subnational tree-seed programmes.

The reporting countries indicated a total of 876 tree species for which reproductive material is produced; Table 14 shows the regional distribution of these species, as well as of species with seed stands and seed orchards and under macro- or micropropagation. Australia and the United States of America did not report registered seed stands, and Canada reported on this aspect for only one species, which explains the low number of seed stands in North America and the Southwest Pacific. Overall, the reporting countries indicated the existence of more than 83 000 seed stands covering about 7 million ha and more than 5 800 seed orchards covering nearly 39 000 ha (Table 15); note, however, that several countries did not report seed stands or seed orchards for all the species included in their tree-seed and tree-breeding programmes.

FIGURE 14

Number of reporting countries with national tree-seed programmes



Note: Based on country reports.

The annual global production of planting stock through macro- and micropropagation exceeds 3.1 billion plants. This is a considerable underestimate, however, because many countries with large areas of planted forests did not report their production. More than 2.6 billion plants are produced annually through macro- and micropropagation in Europe alone (where most countries reported on their planting-stock production).

Sixty percent (46) of reporting countries indicated that they have extension programmes on FGR use (Figure 15); see also the annex); eight countries reported establishing such programmes between 2012 and 2022. The main target group for extension programmes is forest owners (reported by 36 countries), followed by local communities and farmers (Figure 16). Other users targeted by such programmes include forest managers, Indigenous Peoples, nurseries, seed traders and traditional healers.

TABLE 14
Number of tree species, by region, for which forest reproductive material is produced by various means

Basic material	Species reported	Species with seed stands	Species with seed orchards	Species under macro- or micropropagation
Africa	164	124	60	115
Asia	283	184	158	70
Europe	228	188	111	134
Latin America and the Caribbean	149	75	47	15
Near East	na	na	na	na
North America	106	1	31	na
Southwest Pacific	134	1	37	11

Notes: na = not available. Based on country reports.

TABLE 15
Number and area of seed stands and seed orchards, by region

Region	Seed stands		Seed orchards	
	Number	Area (ha)	Number	Area (ha)
Africa	987	16 598	595	1 719
Asia	7 205	45 211	1 253	17 728
Europe	74 359	6 918 078	2 608	18 317
Latin America and the Caribbean	418	13 641	197	709
Near East	na	na	na	na
North America	40	na	948	2
Southwest Pacific	6	2	230	426
Total	83 015	6 993 529	5 831	38 902

Notes: na = not available. Based on country reports.

8.4 Demand for and supply of forest reproductive material

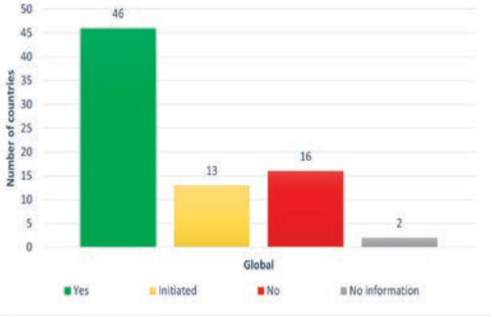
SoW-FGR1 showed that demand for forest reproductive material varies greatly between countries, depending on two main factors (FAO, 2014a):

- Forest management practices – that is, the extent to which forests are regenerated artificially as part of regular forestry operations. Demand is often driven mostly by the establishment of industrial tree plantations, but some countries, particularly in temperate and boreal regions, also regenerate natural forests artificially.
- Large-scale reforestation and restoration programmes targeting previously deforested and degraded areas, and tree-planting efforts such as those to combat desertification. A decade ago, nearly all countries reported actual or projected increases in demand for forest reproductive material and persisting or periodic shortages in its supply (FAO, 2014a).

For this report, countries were invited to provide information on trends in the demand for and supply of forest reproductive material. The submitted information indicates that demand remains strong worldwide and that it is sustained largely by legal or other obligations

FIGURE 15

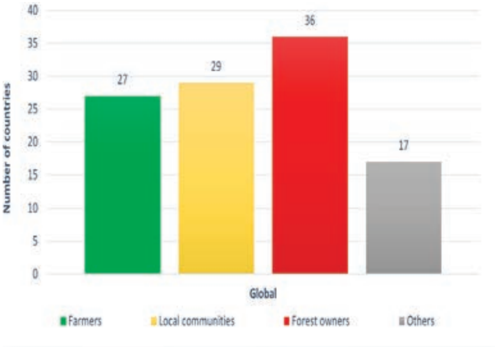
Number of countries with ongoing extension programmes or activities for the use of forest genetic resources



Note: Based on country reports.

FIGURE 16

User types targeted for forest genetic resources extension programmes



Note: Based on country reports.

to regenerate forests after wood harvesting or large-scale damage (e.g. due to fires, storms or mining operations). Efforts to restore forests, conserve biodiversity and mitigate climate change are also maintaining or increasing demand. Many countries noted growing interest in planting native or alternative species to produce wood and non-wood forest products. Many countries reported challenges or shortages in meeting demand.

In China, demand for forest reproductive material is very high, with 15 billion seedlings planted annually. The country reported a considerable increase in the number of nurseries, from 336 000 in 2012 to in excess of 350 000 in 2022 covering more than 1 million ha. The relative share of traditional afforestation and reforestation tree species (e.g. *Abies*, *Acacia*, *Eucalyptus*, *Larix*, *Pinus, Populus* and *Salix* spp.) has decreased since 2012 and that of other species, including native species, has increased significantly.

Other countries in Asia also reported continued demand for forest reproductive material. Japan produces about 65 million seedlings per year, and its report indicated increasing demand for faster-growing and pest-tolerant material and for lower-pollen- and non-pollen-producing varieties of Japanese cedar (*Cryptomeria japonica*; Tsuruta *et al*., 2021) and Japanese cypress (*Chamaecyparis obtusa*). A total of 255 million seedlings were planted in the Republic of Korea between 2015 and 2019 on nearly 120 000 ha. Afforestation and reforestation programmes are also maintaining demand in Sri Lanka, where the Forest Department's nurseries produced nearly 440 000 seedlings in 2021. The country's private sector is also producing planting stock, but those production data are not recorded systematically. Demand for forest reproductive material of certain native tree species, such as teak (*Tectona grandis*), Siamese rosewood (*Dalbergia cochinchinensis*), Burma padauk (*Pterocarpus macrocarpus*) and irul (*Xylia xylocarpa*), increased in Thailand following a 2021 amendment to the Forest Act to promote commercial forest plantations.

In Europe, demand for forest reproductive material is largely to meet legal requirements for reforestation after harvest, although several countries also noted that tree-planting for restoration and biodiversity conservation is increasing. The annual production of seedlings varies between countries, from fewer than 1.5 million seedlings in Slovenia to nearly 800 million seedlings in Poland. The high production in Poland is due to the country's seedling (as well as seed) exports to other European countries, combined with high domestic demand. Other European countries reported much lower annual seedling production: for example, in 2019 Sweden produced 381 million seedlings and Ukraine 265 million.

The reported annual seed harvest also varies considerably among countries in Europe, from a few thousand kilograms to more than half a million kilograms. The seeds are used mostly by nurseries, with direct seeding typically playing a minor role. Nevertheless, direct seeding is a major regeneration method in some European countries. In Finland, for example, the annual demand for forest seeds ranges between 10 000 kg and 12 000 kg, of which most is used for the direct sowing of Scots pine. Nurseries in the country use approximately 1 500 kg of seeds per year to produce between 155 million and 180 million seedlings (mostly *Picea abies*, *Pinus silvestris* and *Betula pendula*). Finnish forestry uses only a few species, but there is interest in increasing the number of species for which forest reproductive material is produced; efforts are underway to bring new species to the market (e.g. by registering *ex situ* conservation units of native hardwood species as seed sources).

In addition to tree-planting initiatives for biodiversity conservation and restoration, demand for forest reproductive material has increased (or is expected to do so soon) in several countries because of the damage sustained in European forests in recent years. Germany reported increased interest in heat- and drought-tolerant deciduous species following damage caused by drought and bark beetles in 2018–2020 to Douglas fir (*Pseudotsuga menziesii*), larch (*Larix* spp.) and Norway spruce in most parts of the country. Germany's report noted that such damage is likely to increase the area regenerated by planting or seeding annually, which is currently about 354 000 ha. Germany's average annual tree-seed harvest amounts to more than 550 000 kg, of which 92 percent consists of heavy-fruited species of oak (*Quercus* spp.), European beech (*Fagus sylvatica*) and sweet chestnut (*Castanea sativa*), with the remaining 8 percent made up of 22 other species. Poland's report mentioned that storm damage in 2017 has increased demand for planting stock, and Italy's report indicated an expectation of increased demand in coming years in response to recent storms and fires, as well as for planned planting programmes as a climate-change mitigation measure.

Slovenia has suffered from large-scale damage to forests caused by sleet and freezing rain in 2014, severe droughts and bark beetles since 2016, and storms since 2017. These events have affected about 60 percent of the country's forest area and 40 percent of the growing stock, posing a considerable challenge because the country's annual seedling production has decreased from about 20 million plants in the early 1990s to fewer than 1.5 million today. The Kingdom of the Netherlands is another rare example of a country in which the production of planting stock has decreased in recent years. There, mean annual production dropped from 29.5 million plants in 2007–2011 to 11.4 million plants in 2013–2016, although the country report indicated that a planned expansion of forest area is expected to reverse this trend.

In Brazil, the restocking of harvested plantations and the establishment of new plantations has kept demand for forest reproductive material high. In 2020, planted forests amounted to 11.2 million ha, of which 78 percent was planted with eucalypts and 18 percent was planted with pines. Other main species included rubber (*Hevea brasiliensis*), acacia (*Acacia* spp.), teak and paricá (*Schizolobium amazonicum*). Brazil reported growing demand for the planting of native species to produce wood and non-wood forest products. Restoration programmes, such as one to restore 15 million ha of degraded Atlantic forest, are expected to further increase demand for the reproductive material of native species. El Salvador reported strong demand for seeds of at least 15 (mostly) native and introduced tree species. The Forest Seed Bank of the Forestry Development Centre produces 65 percent of the seeds used, with the rest supplied by private companies. In 2021, the estimated need in the country was 1 100 kg of seeds to produce 15 million seedlings; the most requested species were madre cacao (*Gliricidia sepium*), teak, mahogany (*Swietenia humilis*), leucaena (*Leucaena leucocephala*) and greenheart (*Colubrina arborescens*).

Strong demand for forest reproductive material was also reported in North America. Canada planted 625 million seedings on 443 000 ha of provincial forest lands in 2021, 9 percent above the ten-year average. Most of the seedlings were of a few species (e.g. *Abies balsamea*, *Pinus contorta*, *P. strobus*, *P. banksiana*, *Picea glauca, P. mariana* and *Pseudotsuga menziesii*), which are used for reforestation as part of commercial forestry operations. Canada further indicated that forest reproductive material is increasingly needed for restoring forests in degraded areas (such as oilfields) and for greening urban environments, such as through the Two Billion Trees Programme, which is bolstering demand across the country. The species planted for restoration and urban greening differ from those used in commercial forestry and require additional seed sources; broadleaved species are generally preferred over conifers. The United States of America reported producing more than 1 billion seedlings annually, of which over 90 percent are conifers, predominantly loblolly pine (*Pinus taeda*) in the southeastern parts of the country and Douglas fir (*Pseudotsuga menziesii*) in the Pacific Northwest. Large-scale restoration initiatives are expected to increase demand for forest reproductive material across the country.

Most countries reported challenges or shortages in the production of forest reproductive material, even those where supply was generally meeting demand. These challenges stem largely from biological and environmental factors that cause large year-to-year variations in seed harvests and make it necessary to store a proportion of the harvested seeds where possible (e.g. during mast years). Although some tree species produce abundant seed crops annually, mast years occur infrequently in many species and the cycle of seed production may last two or even three years, as is the case for most conifers (Schmidt, 2000). Thus, seed crops vary considerably between years, depending on climatic conditions (in the current and previous years). For example, Ukraine reported harvesting 1.4 million kg of seed in 2018 but only 683 000 kg in the following year. In addition to biological and environmental factors, the supply of forest reproductive material is affected by interactions among stakeholders of tree-seed systems and related policies. Work in Ethiopia offers an example of how these systems can be strengthened (Box 8).

Increasing temperatures and more frequent and severe droughts linked to climate change (Allen et al., 2010; Hammond et al., 2022) are likely to stress the seed-production capacity of trees. In addition to causing yearly variation in seed production, harsher climatic conditions could prevent seed maturation. Finland noted that seed production is uncertain in the northern parts of the country, where the low annual temperature sum often limits seed maturation. Finland also reported that years of abundant seed production are irregular throughout the country, especially for Norway spruce, causing periodical seed shortages for this species. Mass collections of spruce cones are organized every 5–10 years to top up the production of seed orchards. Such fluctuations in seed production mean that countries often need to fill shortages in one year with seeds stored from previous years and possibly by importing seeds. France reported that only about 20 percent of the seeds supplied to the domestic market in 2018 originated from the same year's harvest and the rest consisted of 2017 seed stock (74 percent) and imported seeds (6 percent).

In several countries, demand encompasses a large number of species, and this aspect alone creates formidable challenges for securing an adequate supply of forest reproductive material. China reported producing material for 40 timber species, nearly 300 major afforestation species, more than 1 200 landscape species and hundreds of other tree species. Even though

BOX 9

Increasing the supply of high-quality tree seeds in Ethiopia

Investment in the development of integrated tree-seed and seedling supply systems is crucial for tree-planting efforts and ensuring livelihood benefits for those growing trees (Graudal *et al.*, 2021). Such systems comprise tree germplasm itself (seeds or seedlings), and the various stakeholders involved in supply chains, such as tree-seed collectors and producers, tree breeders and tree-nursery managers. An integrated system is one that operates effectively in making high-quality tree-planting material available to growers and facilitating their access to it.

The Provision of Adequate Tree Seed Portfolios (PATSPO) project is supporting the development of an integrated tree-seed and seedling system in Ethiopia. The project began in 2017 to help the country achieve its Bonn Challenge restoration commitment of 15 million ha. It is being implemented by the Center for International Forestry–World Agroforestry with Ethiopian Forestry Development and a range of other national partners, and it is based on priorities identified by government and local communities.

In Ethiopia, inefficiencies in the way in which tree-seed collectors, seed suppliers, nursery growers and others involved in the provision of tree germplasm interact is a major constraint in creating an integrated tree-seed and seedling supply system. PATSPO has brought together key stakeholders in the sector to increase their collaboration. It has built the capacity of stakeholders through training and the development of physical infrastructure. To date, more than 2 500 individuals have been trained in tree-seed collection and procurement methods. The project has also upgraded the facilities of national and local-level tree-seed centres, where essential activities in seed processing, testing, storage and dispatch take place.

PATSPO has established seed sources for a range of native and introduced tree species determined by national stakeholders. These are mostly breeding seedling orchards that supply planting material, enable provenance selection and low-input breeding, and act as FGR conservation collections. Fifty-five stands have been established for 22 species in parallel with the identification, description and registration of already-existing seed sources in Ethiopia (which are the initial focus of suppliers' attention and the starting point of existing tree-seed systems). More than 400 existing seed sources, mostly of native trees, have been registered. Recommendations have been made on appropriate planting locations for these seed sources, both under existing climatic conditions and those predicted for 2050 (Kindt *et al.*, 2024).

PATSPO works closely with the Ethiopian government to develop policies that support the involvement of the private sector – working in cooperation with the public sector – in tree-seed and seedling supply. The work of project partners has shown that the engagement of small and medium-sized enterprises, including community-based entrepreneurs, is essential for developing effective tree-seed and

BOX 9 *CONT.*

seedling systems (Lillesø *et al*., 2018).

To do this effectively needs an enabling environment for these entrepreneurs, which in turn requires policies to support those entrepreneurs with appropriate training in the necessary technical and business management skills and networking opportunities.

Sources: **Cernansky, R.** 2021. Taking root. *Science*, 371: 666–667; **Graudal, L., Lillesø, J-PB., Dawson, I.K., Abiyu, A., Roshetko J.M., Nyoka, I., *et al.*** 2021. *Tree seed and seedling systems for resilience and productivity*. FTA Highlights of a Decade 2011–2021 series. Highlight No. 2. Bogor, Indonesia, The CGIAR Research Program on Forests, Trees and Agroforestry. https://doi.org/10.17528/cifor/008212; **Kindt, R., Abiyu, A., Dawson, I.K., Graudal, L., Lillesø, J-PB., Mengesha, Y., Moestrup, S., Nørgard, C. & van Breugel, P.** 2024. *What to plant where in Ethiopia*. Version for practitioners 2024.07. Nairobi and Addis Ababa, World Agroforestry. (Available at: https://www.worldagroforestry.org/output/what-to-plant-where-in-ethiopia); **Lillesø, J-PB., Harwood, C., Derero, A., Graudal, L., Roshetko, J.M., Kindt, R., *et al.*** 2018. Why institutional environments for agroforestry seed systems matters. *Development Policy Review*, 36: O89-O112.

the country annually collects 6 million kg more seeds than it uses and produces more seedlings than are planted annually, the country report mentioned shortages of planting material for several commercially important species as well as threatened and rare species. In Australia, the production of seeds for commercial plantations meets demand, but there is a shortage of seeds for restoration, which typically requires a wider range of species. Australia's report noted that climate variability, seasonal factors and funding constraints contribute to the shortage.

The demand for forest reproductive material may also arise locally in a country for legal or other reasons, as occurred in Argentina. In Cordoba province, a new agroforestry law requires farmers to afforest 2–5 percent of their land area, and this has increased demand as farmers take action to comply with the law. Nurseries in Cordoba are unable to meet the increased demand, and Argentina's report indicated that nurseries in other provinces are producing seedlings exclusively for Cordoba to meet its heightened demand. At the national level, Argentina also noted difficulties in meeting demand, especially for native and endemic tree species.

Several countries reported filling shortages of forest reproductive material with imports of seeds or seedlings, but this typically covers only a small portion of overall demand and there is large annual variation in imports. Sweden, for example, sourced more than 11 000 kg of seeds externally in the last decade, and Norway imported 3 million seedlings in 2019 to complement the domestic seedling production of 44.5 million plants. Some countries with no significant shortages, such as Australia and Lithuania, also mentioned importing small quantities of material. Others, such as Slovenia and the United States of America, rely on nurseries in neighbouring countries to produce a proportion of their seedling requirements. Slovenian nurseries produce only bare-root seedlings and, when containerized seedlings are required, production is outsourced to a nursery in Austria using Slovenian seeds. The United States of America also reported importing millions of seedlings – raised using United States' seed – from Canada each year for planting on state-owned and privately owned land in the northern parts of the country.

Several countries noted that climate change is expected to affect demand for and the supply of forest reproductive material. In Canada, where the combination of seed-orchard production and wild-stand collections meets demand at the provincial level, suitable areas for both production and collection are being revised in several provinces to take into account the expected impacts of climate change on seed production and demand. The report from Croatia indicated that the country is considering importing forest reproductive material from other European Union countries and even from outside the European Union in the future because of the likely impacts of climate change on its domestic seed production. Ireland noted that it considers it necessary to import forest reproductive material for some species recommended for use in the changing climate because there are few appropriate stands in the country to serve as seed sources for the required species.

8.5 Impacts of climate change on the use of forest genetic resources

Climate change is expected to increase temperatures in continental areas globally at an estimated rate of about 0.27 °C per decade (Hansen, Sato and Ruedy, 2022). Precipitation is expected to decrease in many parts of the world and become more variable (IPCC, 2022b). Severe drought episodes have already increased tree mortality in forests and woodlands (Allen *et al*., 2010; Hammond *et al*., 2022), as has damage by fires (Jain *et al*., 2022). Climate change will also affect the production of forest reproductive material because stressed trees produce fewer seeds, and the seeds produced have reduced germination potential (Alfaro *et al*., 2014; López-Toledo *et al*., 2017).

In their reports, most countries raised concerns or noted uncertainties related to the use of FGR under climate change. Many noted that the changing climate is already creating challenges for procuring and deploying forest reproductive material. These concerns have also received increased attention in recent scientific studies. In British Columbia, Canada, for example, 21 percent of forests are expected to be at moderate to high risk of lacking domestic provenances adapted to the projected climate in 2040; it has been proposed to fill such gaps with seed sources from the Pacific Northwest of the United States of America (O'Neill and Gómez-Pineda, 2021).

The tree populations most vulnerable to drought are those located at the southern (in the Northern Hemisphere) and northern (in the Southern Hemisphere) edges of species' natural distributions, also called the xeric limit (*sensu* Mátyás, 2010). At the opposite edges of the latitudinal distribution, tree growth is limited by low temperatures, and tree populations in these areas are expected to benefit from climate change (if precipitation does not decrease). The same also often applies to the altitudinal range of a distribution: that is, tree populations at low altitudes are typically more frequently stressed by droughts and those at high altitudes are more stressed by low temperatures. Tree populations at the xeric limit are adapted to periodic drought stress, but studies have shown that trees along contemporary xeric limits are increasingly suffering and dying in warmer and drier conditions (e.g. Mátyás, 2010; Mátyás *et al*., 2010).

There is evidence that trees and other woody species are migrating naturally in response to climate change and that the speed of their migration is slow compared with that of climate change. In the United States of America, the natural range centroid of 78 forest understorey plant species shifted an average of 49 km northwards between 1950 and 2000, although the corresponding shift in climate in the same period was 114 km (Ash, Givnish and Waller, 2017). In Europe, holm oak (*Quercus ilex*) – which

Mortality of sacred fir (*Abies religiosa*) trees in Mexico following the extreme dry season of 2024

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grows in drier and warmer sites than other oaks – has expanded in the northern margin of its distribution to sites that were previously too cold and humid for it to compete successfully with other species (Delzon *et al*., 2013).

Trees and other plant species are also migrating along altitudinal gradients. In the Pyrenees mountains of Spain, the timberline of European beech (*Fagus sylvatica*) shifted upwards in elevation by about 43 m between the 1920s and 2003 (a span of about 80 years); meanwhile, the average temperature increased by 1.5 °C, meaning that suitable conditions for the species have shifted upwards in altitude by 200–300 m (Peñuelas *et al*., 2007). Similar findings have been reported for the French Alps, where climate change has resulted in an upward shift in the altitudinal distribution of 171 forest plant species at an average of 29 m per decade; due to their ecological and life-history traits, trees and shrubs were 2–3 times slower than other species (herbs, ferns and mosses) in shifting their distributions (Lenoir *et al*., 2008). These studies indicate that the natural migration of trees and other woody species trails behind suitable climatic conditions and is considerably slower than the velocity of climate change – by one estimate, 6–11 times slower than needed (Gómez-Pineda *et al*., 2020).

Ecological niche models have been applied to contemporary forest biomes and individual tree species to understand potential shifts in distributions due to climate change. In North America, models have predicted reductions in suitable areas for biomes associated with moist and cold climates and the expansion of biomes associated with drier and warmer climates (Rehfeldt *et al*., 2012). In Europe, sessile oak (*Quercus petraea*), one of the two oak species with the largest distributions in Europe, is projected to lose habitat on the southeastern limits of its current distribution in Hungary and Türkiye (Sáenz-Romero *et al*., 2017; Mátyás, 2021). A significant reduction in contemporary distribution, and a shift towards the northeast, has also been projected for Scots pine and Siberian larch (*Larix sibirica*) in Asia and Europe (Tchebakova, Rehfeldt and Parfenova, 2005). Note that although these models predict the extension of species' distributions, trees may be unable to migrate naturally to new climatically suitable areas. Similarly, when models predict reductions in the area suitable for a given species, trees are likely to survive for long periods if their populations are able to cope with or adapt to climatic changes. Therefore, although such models are useful for evaluating the expected impacts of climate change, forest managers should consider their projections along with other relevant information.

In addition to monitoring changes in distributions and projecting such changes, much research has focused on understanding local adaptation by investigating genetic differentiation of tree populations along environmental gradients (e.g. Rehfeldt, 1988; Rehfeldt *et al*., 1999). Although many tree species grow across large geographical areas with diverse environmental conditions, individual populations of a given species are frequently adapted to narrower ranges of conditions. This population-level differentiation can be assessed by growing provenances of trees originating in different climates in common garden trials (see Chapter 5). For example, it is possible to estimate how large a difference in altitude is needed to make two populations statistically different for genetically controlled quantitative traits such as height growth, resistance to frost damage, and biomass growth (Rehfeldt *et al*., 2018). It has been shown that the altitudinal difference is 240 m in Douglas fir, 300 m in lodgepole pine (*Pinus contorta*), 420 m in Engelmann spruce (*Picea engelmannii*) and 450 m in whitebark pine (*Pinus albicaulis*) (Rehfeldt, Warwell and Monserud, 2020). Other studies have reported a difference of 200 m for ocote pine (*Pinus oocarpa*) (Sáenz-Romero, Guzmán-Reyna and Rehfeldt, 2006) and Mexican weeping pine (*P. patula*) (Ruiz-Talonia *et al*., 2014), 300 m for smooth-bark Mexican pine (*P. pseudostrobus*) (Sáenz-Romero *et al*., 2012), 350 m for sacred fir (*Abies religiosa*) (Ortiz-Bibian *et al*., 2017) and 400 m for Michoacan pine (*P. devoniana*) (Sáenz-Romero and Tapia-Olivares, 2008). These altitudinal-difference values can be used as proxies for climate clines. The average of the above-listed values is 318 m, which is equivalent to about 1.5 °C, representing a relatively narrow part of the climatic continuum occupied by each species. This means that many tree populations will soon experience climatic conditions beyond their historical climate clines because the global surface temperature is expected to reach 1.5 °C above 1850–1900 levels by the mid-2030s (IPCC, 2023). In fact, the +1.5 °C threshold was surpassed in 2023–2024, due in part to the impact of the El Niño Equatorian warm Pacific Ocean stream (Hansen, 2024; Sáenz-Romero, 2024).

Climate change poses a dual challenge for the use of FGR because forest reproductive material deployed today needs to be able to thrive at a given site under both the present and future climates. Historically, seeds have often been collected within a deployment area based on an assumption that local seed sources are best (or at least among the best). Provenance trials have shown, however, that local provenances are not consistently best and that climate change is making that assumption even more problematic (e.g. Ledig and Kitzmiller, 1992; Sáenz-Romero *et al*., 2016). “Local” has been defined and understood in various ways. Early guidelines promoting the use of local seeds limited transfer distances to 160 km and altitudinal difference to 330 m between the seed-collection and deployment sites (e.g. McCall, 1939). More elaborate deployment guidelines have since been developed based on multiple seed zones and subzones along latitudinal, longitudinal, elevational and moisture gradients (e.g. Buck *et al*., 1970; Millar and Libby, 1991).

In the present circumstances, it would be wise to adjust deployment zones based on the occurred and projected changes in climatic conditions, taking into account the long harvesting cycles (typically several decades) in forestry and, in the case of restoration plantings for biodiversity conservation, the even longer life cycles of trees. An example of such an approach is in British Columbia, Canada, the climate-based seed-transfer system of which recommends transferring seeds a climate distance equivalent to the amount the climate has changed since a normalized reference period (1931–1960 in

British Columbia), plus the expected climate change in the 15 years after planting (which, in British Columbia, is one-quarter of the rotation period) (O'Neill *et al*., 2017). Given that rotation age varies among species and even provenances, a transfer distance should be defined for each. Canada reported that several other provinces have also adopted this approach, which is creating complexity in the sourcing and deployment of forest genetic material and for tree breeding. An alternative to calculating specific transfer distances is the revision of deployment zones based on projected climate change, as is the case in Mexico (Castellanos-Acuña *et al*., 2018).

Regardless of the approach used to define deployment zones, it is crucial to use genetically diverse material with the capacity to adapt to current and future conditions and to avoid a narrow view of what is "local" (Broadhurst and Boshier, 2014). Provenance mixes can be used to increase genetic diversity in the deployed material (see Breed *et al.*, 2013, for a review of seed sourcing strategies). Such mixing is often considered insurance against uncertainties about future climatic conditions. Increasing the number of species planted in a location (Kindt, 2023), and even replacing the currently used species (Whittet *et al*., 2016), are other possibilities.

Several country reports mentioned ongoing efforts to re-evaluate existing provenance trials (and sometimes to establish new ones) to guide the deployment of forest reproductive material in the face of climate change. Such analyses can provide a better understanding of local adaptation and how tree populations respond to climate change. This is important, not only for the establishment of new planted forests but also for the management of naturally regenerating forests under climate change and the sourcing of seeds from these forests.

The transfer of forest reproductive material involves risks to the survival and growth of trees. Based on long-term progeny and provenance tests (planted in 1912) of Douglas fir at multiple sites in the western United States of America, St.Clair *et al*. (2022) found that, for the deployment of provenances in colder sites, losses in terms of survival and growth would be acceptable, even with climatic transfer distances (i.e. the difference between the mean annual temperature of seed sources and that of the deployment sites) of up to 2–3 °C. Based on their evaluation of multiple provenance trials of five important eastern North American tree species (*Picea glauca*, *P. mariana*, *Pinus banksiana*, *P. strobus* and *Betula alleghaniensis*), Pedlar, McKenney and Lu (2021) reported, however, that optimal height growth could be achieved with a modest average warm-to-cold (generally northwards) transfer of 1.6 °C. Castellanos-Acuña, Lindig-Cisneros and Sáenz-Romero (2015) estimated a loss of 5 percent in height growth in *Pinus pseudostrobus* (smooth-bark Mexican pine) for every 100 m (or 0.5 °C) of upward transfer, based on reciprocal common garden tests along an altitudinal gradient in Mexico. Carbajal-Navarro *et al*. (2019) suggested that provenances of *Abies religiosa* (sacred fir) could be transferred up to 400 m upwards in the Monarch Butterfly Biosphere Reserve in Mexico, provided that the seedlings were planted under the protective shade of shrubs. Species range expansion by assisted migration of *Abies religiosa* beyond its natural upper altitudinal limit could be done up to 2.3 °C toward colder sites or by shifting about 500 m upwards in elevation, with a drop in survival of 21 percent and a reduction in seedling height of 47 percent, compared with the survival and growth at a field site equivalent to a zero climatic-transfer distance (Sáenz-Romero *et al*., 2024).

The use of FGR in the changing climate necessitates three types of germplasm transfer in reference to a species' contemporary distribution, as follows (Dumroese *et al*., 2015; Ipinza Carmona *et al*., 2022; Sáenz-Romero *et al*., 2021): (1) deploying provenances within the natural distribution range of the species; (2) transferring provenances outside the current range of the species (also called range expansion); and (3) transferring provenances to sites far away from the contemporary distribution to where projected climatic conditions are suitable.

These three transfer types can be applied for both production and conservation purposes, but the third is likely to be considered only in exceptional cases. For example, Florida torreya (*Torreya taxifolia*), a critically endangered conifer that grows naturally in only one glacial refugium in the southeastern United States of America, has been proposed for translocation about 500 km northwards (McLachlan, Hellmann and Schwartz, 2007).

Technically, such transfers do not differ much from past practices applied to the transfer of FGR in different parts of the world, primarily to produce wood and non-wood forest products. The new element, however, is the aim to facilitate the adaptation of tree populations to climate change; this concept has been variously labelled assisted migration, assisted colonization, assisted relocation and facilitated migration (Rehfeldt *et al*., 2002; Aitken *et al*., 2008; Hewitt *et al*., 2011; Pedlar *et al*., 2012; Tchebakova, Rehfeldt and Parfenova, 2005; Dumroese *et al*., 2015). It has been widely debated, and the attitudes of forest managers, conservationists and the public to assisted migration vary depending on the geographical distance of proposed transfers. Transfers within the natural distribution of species are often accepted, but they are more controversial in cases of range expansion and especially far-away translocation (Peterson St-Laurent *et al*., 2019).

Because transferring provenances within the natural distribution of tree species is already a common forestry practice, assisted migration is generally accepted among forest managers. Conservationists who consider minimum human intervention, or no intervention at all, as the best way to ensure the adaptation of ecosystems may perceive assisted migration as too extreme and therefore undesirable. There are other reasons for objecting to assisted migration, including rules or even laws prohibiting the transfer of a species or its provenances to protected areas where it does not occur naturally, even when assisted migration might save an endangered species from extinction. It is likely that the debate on assisted migration will continue and positions could change as the impacts of climate change and other pressures on FGR increase.

8.6 Needs, challenges and opportunities

Countries reported various needs in relation to the production of forest reproductive material. Most considered increasing the supply of material, especially improved material, as the main priority to meet current or projected demand. Several countries also mentioned that there is a need to increase end-user awareness of the advantages of using high-quality and well-documented germplasm. Some noted that a broader assessment of future needs in the forest sector is necessary to identify possible new species suitable for cultivation.

Several countries identified a need to revise approaches and guidelines for the deployment of forest reproductive material because of climate change, and others mentioned that such revisions have been initiated or have concluded. Some countries with no national or subnational strategies or guidance for FGR use noted that provenance selection and the use of improved material are open to interpretation and applied inconsistently at the local level. Some countries also indicated that government agencies, commercial forest companies and other forest owners may follow different recommendations for the deployment of material. Many countries stressed the need to improve the documentation and traceability of material throughout supply chains, including deployment sites. Various digital tools could be used for this purpose, such as MyFarmTrees, which has been piloted in Cameroon and Kenya. Keeping a record of the materials used at different sites enables later assessments of how a given material has performed in practical forestry under changing climatic conditions.

Several countries indicated that attention is needed to overcome difficulties in producing high-quality planting stock in nurseries. Some also noted that nurseries would benefit from the improved availability of market information (e.g. customers' planting targets) so they can better plan production to meet demand.

The production of forest reproductive material involves many biological, technical and logistical aspects that can disrupt supply if not adequately addressed. A lack of policies governing the production of suitable material, or poor implementation of existing policies, hampers the efforts of countries to increase the availability of high-quality, well-documented germplasm. Most countries reported challenges related to these aspects and resultant shortages in the availability of forest reproductive material or difficulties in maintaining current levels of supply.

Because climate change is expected to alter the flowering patterns of trees and the timing of seed maturation, several countries indicated that they are prepared for additional challenges in organizing seed collection from both wild stands and seed orchards. Many countries also noted challenges (due to shortages of funding and qualified personnel) in establishing new seed orchards to replace ageing ones. Seed-orchard management is also challenged by poor flowering and damage by insects and pathogens.

Countries listed their priorities for capacity building. Many, especially those with ageing human populations, noted difficulties in replacing existing skilled staff with specializations in seed collection and handling, seed-orchard management and nursery production. The number of operators involved in collecting seeds and producing forest reproductive material decreased in several countries in the last decade. In many countries, this erosion of human and institutional capacity is likely to cause significant problems for plans to increase the production of forest reproductive material.

Another concern is a decrease in nursery area over the last decade, as reported by a few countries. It is unclear, however, whether this is because of the ongoing shift to containerized seedlings in nursery production in those countries or because forest nurseries are struggling with their financial sustainability, despite strong demand for planting stock.

Increased interest in broadening the selection of species for which forest reproductive material is produced offers opportunities to enhance FGR use. Although many new species included in national tree-seed programmes are used primarily for restoration and biodiversity conservation, some also offer economic opportunities if brought under cultivation and genetic improvement (see examples in Chapter 1). Moreover, several tree species grow scattered in natural forests or agricultural landscapes for which large quantities of viable seeds are difficult to obtain from wild populations. For such species, some countries are considering the establishment of *ex situ* seed-production stands using grafted clones of known parents or wildings. When *ex situ* conservation units exist, they can also be registered as seed stands.

Some countries noted that, although climate change presents challenges, it also offers opportunities. For example, seed maturation may benefit from increasing temperatures in areas where low temperatures have been a limiting factor. Increasing temperatures and changing precipitation patterns will probably also create more favourable conditions for tree growth in some locations. As discussed above, climate change makes it possible to introduce new species or provenances to produce specific products and for other purposes.

Imports of forest seeds and other reproductive material play a relatively small role in most countries in meeting demand for new forest establishment, and importing countries mostly reported buying material from neighbouring countries or other countries in the same ecoregions. Imports of the forest reproductive material may increase in the future, however, especially in those countries unable to increase their own production. Several countries noted increasing interest – due to climate change – in using species and provenances for which they do not have seed sources. This offers export opportunities for countries that can continue to produce more material than they need and which have reliable certification systems in place.

8.7 Conclusions

Globally, demand for forest reproductive material has remained strong and has diversified in terms of species. In many countries, the supply of material does not meet demand, and the availability of forest reproductive material is limited in terms of both quantity and quality. This poses a problem for ongoing efforts to improve people's livelihoods by establishing new forests to produce wood and non-wood forest products, conserve biodiversity and mitigate climate change. Even those countries with well-functioning national tree-seed programmes reported periodic shortages in the supply of forest reproductive material. Countries largely rely on their domestic production, and seed and seedling imports typically cover only a small proportion of overall demand – although this may change because several countries are considering the option of increasing imports to meet demand.

Progress in developing or reinforcing national tree-seed programmes has been modest over the last decade. Most national tree-seed programmes were established several decades ago, and many developed and developing countries reported that only limited financial and human resources are available for running these important programmes. Despite the challenges, nearly all reporting countries noted that increasing the supply of material remains a priority.

Globally, unimproved germplasm has retained its dominant role in the production of forest reproductive material. Improved germplasm is produced in almost all reporting countries, but its availability varies considerably. The continued large-scale use of unimproved germplasm means that countries cannot benefit from the productivity gains and pest and disease resistance that improved material can provide. Several countries mentioned that end-users are often unaware of the advantages of using high-quality, well-documented germplasm.

Climate change is bringing challenges and opportunities, not only for the deployment of forest reproductive material but also for its production. This means that countries need to deal with additional complexity when using FGR. Based on provenance trials and other research efforts, several countries have revised their deployment guidelines to take climate change into account, and others have initiated such revisions. Few countries have evaluated the impacts of climate change on seed production and harvesting, however. This aspect should be assessed carefully, especially in areas where tree populations are becoming more stressed because of climate change.

Climate change is also likely to increase the international trade of certified and well-documented forest reproductive material because several countries are interested in cultivating species and provenances for which they do not yet have their own seed sources. Currently, however, few countries can offer such material in international markets, and they may have less surplus material in the future.

Chapter 9

State of tree-improvement and tree-breeding programmes

9.1 Introduction

Although many woody plant species, especially fruit- and nut-bearing species, have been the subject of informal selection for millennia (Burley, 2004), genetic improvement and breeding for forestry has a much shorter history. Following early provenance trials in the eighteenth and nineteenth centuries to identify suitable tree species and their seed sources for reforestation (König, 2005), the first tree-breeding programmes for timber production were initiated in the 1930s (Hitt, 1952). By the 1950s, many countries, especially in Asia, Europe and North America, had set up formal and often government-supported tree-breeding programmes (FAO, 2014a). These early breeding efforts involved the mass selection of desired phenotypes (or plus trees) in the wild and the collection of propagules for establishing progeny or clonal trials and orchards. In the 1970s, tree-breeding programmes started developing recurrent selection strategies to advance the single-generation approach, in which individual parent trees in seed orchards were culled based on the results of progeny tests (Burley, 2004). Many of the tree-breeding programmes stopped at the first generation of selection, however (Namkoong, Barnes and Burley, 1980).

Tree breeding is carried out typically using the classical recurrent selection approach involving repetitive cycles of breeding, testing and selection. Tree breeding differs from crop breeding in several ways, however. First, tree breeders face challenges due to the biological peculiarities of trees, such as high genetic diversity (outcrossing), late sexual maturity and long regeneration cycles (FAO, 2014a). Moreover, tree species are largely undomesticated, meaning that tree breeders usually start working with wild populations rather than known varieties selected and cultivated by farmers. Most tree-breeding programmes aim for gradual population-level improvement rather than the development of new varieties, which is the case in crop breeding. Because tree breeders work with long time horizons, they attach great importance to safeguarding genetic diversity in breeding populations to insure against pests and diseases, catastrophic events and changes in market demand (FAO, 2011). Tree breeders have developed solutions such as grafted archives at multiple locations, the separation of breeding and deployment populations, and multiple population breeding strategies to simultaneously enable the conservation of genetic diversity and genetic gains (FAO, 2011).

SoW-FGR1 analysed the state of tree improvement and breeding programmes and reviewed current and emerging technologies in this field (FAO, 2014a). It found that tree breeding was conducted in all regions of the world, albeit at differing levels of intensity and investment, and was making significant contributions to sustainable forest management and providing improved germplasm for the production of wood and other forest-based products. It also showed that about 730 species were subject to improvement efforts globally and that improved germplasm had been made available for the production of wood and non-wood forest products, increasing productivity by 10–60 percent depending on species, targeted products (e.g. wood, fruit or resin) and breeding generation. Although early tree-breeding efforts focused on wood-production-related traits such as growth rate, wood quality and tree form, in recent decades some breeding programmes have given more weight in their selection goals to adaptability-related traits such as resistance to drought, fire, pests and diseases.

SoW-FGR1 stressed the potential of tree-breeding programmes to increase the productivity of planted forests to meet growing global demand for forest products and to provide improved germplasm for forest restoration. Moreover, it revealed that modern technologies such as marker-assisted selection, genomic tools and genetic modification (GM) were increasingly being applied to reduce the time and cost of conventional tree breeding. Nevertheless, there is huge untapped potential to improve forest product quantity and quality and the adaptive traits of trees and other woody species because only a small fraction of these species has been studied for breeding purposes (FAO, 2014a).

The importance of tree improvement and breeding was stressed in the Global Plan of Action (FAO, 2014b), which called for the reinforcement of tree breeding and related activities to unlock the full potential of FGR and promote the use of emerging technologies to support FGR development. This chapter presents an update on the state of tree breeding and analyses the progress since SoW-FGR1.

9.2 State of tree-breeding programmes

Organization of tree-breeding programmes

Tree-breeding programmes,[20] including government-funded national initiatives and private and academic efforts, rely for their success on collaboration among diverse entities, such as government agencies, research institutes and the private sector. Improved coordination among these actors is essential for fully harnessing genetic improvements for sustainable forest management (FAO, 2014a). Tree-breeding programmes also play vital roles in ecological restoration and help combat deforestation and mitigate the impacts of climate change (Ray *et al*., 2022). Modern approaches such as genomics and genetic engineering can increase the precision and efficiency of these programmes (Ray *et al*., 2022).

For this report, 58 countries (75 percent of reporting countries) indicated that they had operational tree-breeding programmes in place (Figure 17; see also the annex).

The main stakeholder groups operating tree-breeding programmes are public entities, private companies and public–private partnerships (Figure 18); others include registered charities and non-profit associations. In their reports, many countries indicated that collaboration among government institutions, universities, private enterprises and consortia, within and between countries, is a cornerstone of successful and well-coordinated tree-breeding programmes. It is essential for consolidating germplasm, expertise and knowledge.

In Argentina, tree-breeding programmes involving both native and introduced species have been advanced by universities, research centres, forest companies and Instituto Nacional de Tecnología Agropecuaria (National Institute of Agricultural Technology). Brazil is another country in which a broad spectrum of stakeholders collaborates in tree breeding, with concerted efforts between research institutions (e.g. Embrapa), universities and private entities to improve the genetic resources of introduced and native forest species. Initiatives such as the Pravaler project and the WebAmbiente platform by Embrapa and the Ministry of Environment also show the country's multifaceted approach to environmental restoration and forest

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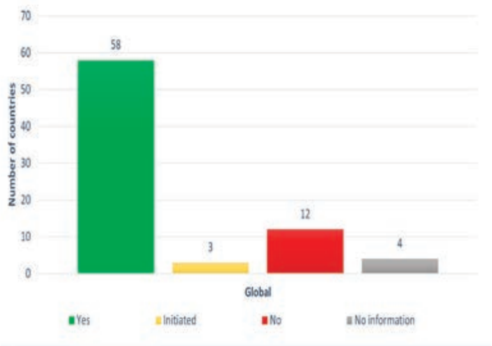
[20] Tree-breeding programmes are systematic efforts based on the application of genetic principles and practices to develop improved trees. A tree-breeding programme may be public, private or a private–public partnership and may operate at the subnational, national, regional or global scales.

FIGURE 17

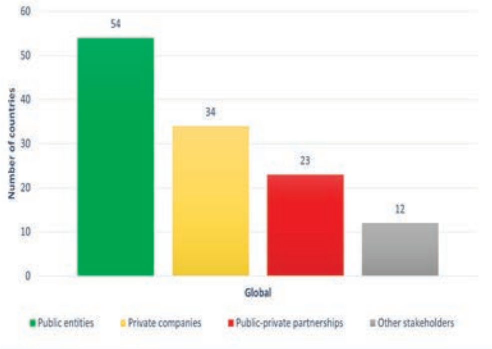
Number of countries with operational tree-breeding programmes



Note: Based on country reports.

FIGURE 18

Main stakeholder groups operating tree-breeding programmes



Note: Based on country reports.

management. In convening workshops and courses and establishing gene banks, the aim of these initiatives is to conserve and develop FGR and promote sustainable forestry practices that meet demand for high-quality raw material. In its report, Sweden also indicated that tree breeding is a joint effort among all forest-owner categories, supported by the government and managed by Skogforsk (Forestry Research Institute of Sweden). Research programmes are negotiated every four years, with inputs from advisory groups representing stakeholders. Sweden's report further noted that funding for seed-orchard programmes has shifted from the government to private sources.

International and regional cooperation in tree breeding is important for enabling countries to manage their breeding programmes in a cost- and time-effective manner and to ensure the availability of germplasm for future breeding efforts. Several countries mentioned Camcore, based at North Carolina State University, and TreeBreedex, a European consortium, as examples of international cooperation in tree breeding. Camcore focuses on the genetic improvement of pines, eucalypts, gmelina and teak in Africa, Asia, Latin America and North America, and it is also engaged in FGR conservation and technology development, with an emphasis on *ex situ* conservation through its partners. Zimbabwe reported benefiting from the work of Camcore, with two companies there engaged in its provenance evaluation programmes. TreeBreedex fosters collaboration among European research teams by focusing on breeding-material management, strategy optimization and variety dissemination. The TreeBreedex database encompasses over 300 000 genotypes and 7 600 experimental sites across Europe for 117 taxa. Croatia's report mentioned the absence of a robust organizational framework for tree breeding capable of fully addressing challenges, establishing strategic objectives and ensuring long-term management. Cooperation can also be with neighbouring countries: for example, Serbia reported successful cross-border collaboration in tree breeding among the Western Balkans countries. Breeding programmes in Finland and Sweden exchange breeding material and performance data for *Pinus sylvestris* and *Picea abies*, and the two countries have also developed a web-based deployment guidance tool.

Several countries noted the importance of national tree-seed centres for tree breeding (see also Chapter 7). In El Salvador, efforts are underway to fully fortify the Centro de Desarrollo Forestal Regional Forest Seed Bank as part of the RECLIMA ("Upscaling climate resilience measures in the dry corridor agroecosystems of El Salvador") project, which supports climate resilience measures in the agroecosystems of the country's dry corridor. This seed bank, in San Andrés, houses 56 seed sources for 39 species with the aim of meeting commercial tree-seed demand, enhancing the genetic traits of commonly used species, and conserving endangered species. Canada also noted the contributions of its national tree-seed centre in sharing seeds for research purposes, both inside the country and internationally.

The evaluation of genetic diversity and breeding strategies in Europe highlights the need to maintain a broad gene pool to ensure resilience in the face of environmental change (Olsson *et al*., 2023). Incorporating diverse genetic material into breeding programmes and employing genomic selection techniques can significantly increase the adaptability of tree species to shifting climate patterns, thereby supporting forest ecosystem sustainability and improving tree health and productivity (Olsson *et al*., 2023). Testing breeding materials in diverse environmental conditions is essential for optimizing adaptive traits (Fugeray-Scarbel *et al*., 2024).

In their reports, countries mentioned challenges in accessing tree germplasm, monitoring susceptibility to pests and diseases, developing cost-effective phenotyping methods, and integrating breeding with product evaluation and development. Several countries noted that limited resources – that is, funding constraints and a scarcity of expertise – are hindering tree breeding. The country reports also indicated that, although commonalities exist in approaches to tree improvement and breeding, each strategy is tailored to the specific needs, ecological conditions and economic priorities of the respective country or private company.

TABLE 16

Number of species included in tree-breeding programmes, by region

Region	Number of species*
Africa	86
Asia	185
Europe	112
Latin America and the Caribbean	108
North America	69
Southwest Pacific	51

Note: Based on country reports.

Species included in breeding programmes

In total, the reporting countries indicated that nearly 500 species are included in tree-breeding programmes (Table 16 shows the regional distribution). SoW-FGR1 reported about 730 species and subspecies, but it is likely that the actual number of species in tree-breeding programmes has not changed significantly in the last decade – the difference between the two reports is likely due to the fewer number of reporting countries for the present report and the requirement for countries to report only at the species level. It could also be that interest in some species has declined.

Pines (*Pinus* spp.) are the most targeted species for tree-breeding programmes in all regions except the Southwest Pacific (Table 17). Other conifers, such as *Abies*, *Picea* and *Larix* species, are also the focus of breeding programmes, especially in Europe and North America. Of broadleaved species, oaks (*Quercus* spp.) are actively bred in Asia, Europe and North America. Acacias and eucalypts are well-represented in breeding programmes across Africa, Asia, Latin America and the Caribbean, and the Southwest Pacific. Other fast-growing species, such as *Populus* and *Salix*, are subject to breeding programmes in Asia, Europe and Latin America and the Caribbean. Native tree species in the genera *Cedrela* and *Nothofagus* are targeted in Latin America and the Caribbean.

Breeding approaches

Tree breeding is a long-term activity requiring research infrastructure, well-trained human resources and financial investment by countries and stakeholders. Recurrent selection is still the most common breeding approach, as reported by countries, although it has been applied to a relatively small number of economically important species for which breeding programmes have

TABLE 17

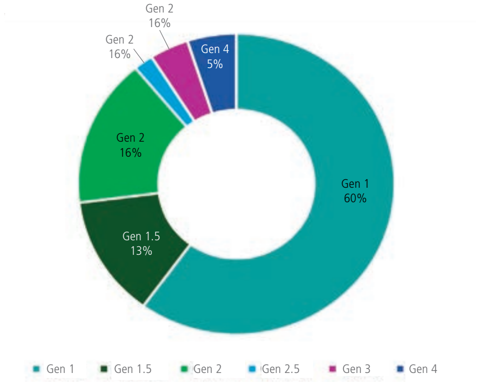
Top five genera per region reported in tree-breeding programmes

Region	Genus	No. of reported species
Africa	*Pinus*	14
	Eucalyptus	6
	Acacia	4
	Khaya	4
	Rhizophora	3
Asia	*Pinus*	14
	Quercus	7
	Populus	7
	Eucalyptus	7
	Acacia	5
	Betula	5
Europe	*Pinus*	17
	Populus	7
	Quercus	7
	Abies	6
	Larix	6
Latin America and the Caribbean	*Pinus*	27
	Eucalyptus	16
	Nothofagus	6
	Cedrela	5
	Salix	4
North America	*Pinus*	14
	Quercus	10
	Abies	6
	Picea	5
	Larix	4
Southwest Pacific	*Eucalyptus*	23
	Pinus	4
	Corymbia	4
	Santalum	4
	Acacia	3

Note: Based on country reports.

FIGURE 19

Distribution of species by generation number deployed for the production of forest reproductive material



Note: Based on country reports.

advanced beyond first-generation selection. Breeding programmes for 60 percent of the reported species are still at the stage of first-generation selection; another 16 percent of species are in the first-generation stage but seed orchards have been culled based on progeny tests. Third- and fourth-generation selections have been deployed for the production of forest reproductive material for a combined 9 percent of the species (Figure 19). Six countries (Australia, Guinea, Italy, Lebanon, Portugal and Zimbabwe) in four regions reported the deployment of material from fourth-generation selections. The breeding of loblolly pine (*Pinus taeda*) has also reached the fourth selection cycle in the United States of America but the material is not yet deployed for production (McKeand *et al*., 2021; Fikret and McKeand, 2019). A decade ago, the most advanced breeding programmes had already reached the fourth generation (FAO, 2014a), so the situation has not changed in this regard.

SoW-FGR1 showed that hybrid breeding, encompassing interspecific hybrids and wide provenance crosses, was also a widely applied approach for enhancing productivity and introducing genes for disease resistance (FAO, 2014a). For the present report, countries in all regions except the Near East reported a total of 34 unique hybrids. European countries reported 19 hybrids, followed by Asia (7 hybrids), Latin

America and the Caribbean (4), Southwest Pacific (3), North America (2) and Africa (1). The reported hybrids were in various genera, including *Acacia*, *Eucalyptus*, *Fagus*, *Juglans*, *Larix*, *Nothofagus*, *Picea*, *Pinus*, *Platanus*, *Populus*, *Quercus* and *Salix*. In Europe, the most reported hybrids were from *Juglans, Larix* and *Populus*, and in Latin America and the Caribbean they were from *Eucalyptus*. North America reported mostly *Picea* hybrids, and Asia and the Southwest Pacific reported *Acacia* hybrids. The only reported hybrid in Africa was *Rhizophora x harrisonii*.

Tree breeding uses grafting, micropropagation, somatic embryogenesis and hormone application to promote early flowering in seed orchards. Cloning is also a useful method for producing large numbers of improved planting stock at low cost. Twenty-four countries mentioned *in vitro* culture techniques, together with vegetative propagation. These techniques were mostly reported by countries in Asia, Europe and North America. Some countries, such as Canada, mentioned testing the efficacy of genomic selection in the process of planting significant numbers of vegetatively propagated trees (both rooted cuttings and somatic emblings). Spain noted that the approaches used for tree improvement and breeding differ among species and areas but that the focus is on the deployment of improved material from seed orchards and clonal propagation in special cases (e.g. chestnut, oaks and pines).

Argentina has a longstanding tradition of genetic improvement in *Populus* and *Salix* through hybridization, with recent efforts expanding to the cultivation of *Pinus elliottii* and *P. caribaea* hybrids, along with the development of cold-resistant eucalypt hybrids (Marcó *et al*., eds, 2016). Species from the *Neltuma* genus, which can cross and produce hybrids, are planted widely and are a key focus of genetic improvement programmes (López Lauenstein *et al.*, 2021). Since the 1970s, tree breeding has encompassed the conservation and domestication of native species, beginning with *Araucaria angustifolia* and later involving *Prosopis*, *Nothofagus*, *Austrocedrus*, *Cordia*, *Handroanthus* and *Cedrela* (Pastorino and Marchelli, 2021). Brazil reported the existence of vegetative propagation programmes for eucalypt hybrids that are used primarily in the timber, pulp, paper and charcoal industries due to their high productivity and uniformity. These programmes have led to higher survival rates and notable gains in productivity for the above-mentioned purposes.

Systematic evaluations and genetic improvement have been conducted for a large number of tree species, including 185 species in China alone. Molecular-assisted breeding methods have become instrumental to achieving progress in China and Japan, aided by sustained long-term funding. China has also made significant progress in breeding cultivars and varieties such as *Populus* "Bo Feng" and "Yi Yang" and more than 20 cultivars of *Camellia sinensis*, which is endemic to the country. Thailand's domestication and breeding programmes for non-wood products are being advanced for various tree species, including pines, *Phyllanthus emblica*, *Gluta usitata* and agarwood (*Aquilaria* spp.).

Australia is the only country in the Southwest Pacific region that provided additional information on tree-breeding programmes. Tree Breeding Australia, established in 1983, oversees cooperative national initiatives focused on radiata pine (*Pinus radiata*) and southern blue gum (*Eucalyptus globulus*). It also provides database services and quantitative analysis for shining gum (*E. nitens*) and other commercial plantation species. Forest and Wood Products Australia has funded various tree-breeding projects: notably, the Eucalypt Sources for Timber Research database contains comprehensive information on trials of Australian eucalypt species, including their genetic and silvicultural backgrounds. These trials present potential avenues for future research in solid-wood processing and associated products.

In the Kingdom of the Netherlands, the *Ulmus* breeding programme, which focuses on disease-resistant hybrids for urban and landscape use, has released four varieties ("Fagel", "Klondike", "Nikko" and "Europa") with strong resistance to Dutch elm disease (DED). In addition, eight

Populus x canadensis clones have been selected from trials for further testing. In the United States of America, *Ulmus americana* breeding is targeting disease-resistant varieties for urban landscapes, and *Juglans cinerea* is undergoing genetic testing and regeneration to combat butternut canker.

Breeding without breeding is an innovative concept that allows significant genetic gains in short periods without the need for controlled pollination or extensive field testing (El-Kassaby and Lstibůrek, 2009). The method combines the use of phenotypic or genotypic pre-selection of superior individuals to minimize fingerprinting efforts, pedigree reconstruction of offspring to assemble naturally created full- and half-sib families, and quantitative genetics analyses to identify elite genotypes (El-Kassaby and Lstibůrek, 2009). The method is showing promise as a means for compensating uncertainty in offspring selection when pedigree data on parental stocks are incomplete. It relies on sequence information in the form of complete pedigree information from a subset of offspring with known maternal parents and molecular markers. The approach captures up to 85 percent of the genetic response to selection achieved through conventional breeding programmes but without the need to perform controlled crosses or experimental field testing, which are costly and time-consuming (FAO, 2018c).

9.3 Recent advances in tree breeding and related research

SoW-FGR1 found that new technologies in use in tree breeding such as QTLs and marker-aided selection are increasingly powerful options for selection (FAO, 2014a). The diversity of native and introduced tree species included in breeding programmes reflects the varied ecological needs and economic uses of trees in different regions. Traditional breeding methods, such as selection, seed-orchard establishment and progeny testing, are used widely, but there is a notable shift towards the incorporation of modern techniques. Whole-genome sequencing (WGS), genome-wide association studies (GWAS) and transcriptomics are being used increasingly to map valuable traits in tree species to address environmental challenges. The increasing use of genomic tools such as molecular genetics, genomics, marker-assisted selection (MAS), *in vitro* culture and novel approaches such as gene editing and whole-genome sequencing shows the strong interest in enhancing breeding efficiency. The pursuit of advanced tree-breeding programmes is leading to the blending of enduring traditional practices and cutting-edge technologies (see also Box 8 in Chapter 7 on tree diversity breeding).

Many countries reported using both existing and novel technologies in tree breeding. In Argentina, conifer and eucalypt breeding has advanced with genomic selection, QTL detection and marker-assisted breeding. The United States of America noted continued interest in pest and disease resistance that also supports conservation goals. The country is exploring advanced technologies such as hyperspectral imaging for detecting fungal infections in trees and drones for measuring trees in field trials. In its report, the United States of America suggested that, although genomic resources enhance breeding efficiency, the successful use of these resources requires new tools, such as gene editing, as well as computational resources and bioinformatics expertise. The report also noted the role of international collaboration in the genome sequencing of forest tree species, such as poplars, eucalypts, American chestnut, willows and pecan, and indicated that microbial genomes linked to forest trees have been sequenced, with global partnerships exploring microbe interactions with forest tree growth and physiology.

Marker-assisted selection

SoW-FGR1 (FAO, 2014a) explored the potential of MAS in tree breeding and its application in well-studied breeding populations under genetic improvement. QTL analysis that primarily targets growth traits with relatively low heritability and controlled by multiple genes requires marker-saturated linkage maps and phenotypic measurements for success. SoW-FGR1 concluded that, although QTL mapping has successfully identified loci accounting for a noticeable variance in traits in some species, the practical application of MAS for enhancing productivity and growth is challenging due to the complex and variable nature of the component traits.

MAS involves identification of specific genetic markers associated with desirable traits that serve as indicators for the presence of favourable genes without the need to conduct traditional testing. MAS enables breeders to select trees with desired characteristics much earlier in the life cycle (Ahmar *et al*., 2021). QTL research in trees focuses on identifying and mapping the regions of the genome (i.e. loci) associated with quantitative traits. Quantitative traits such as tree height, wood density, disease resistance and other economically and ecologically important characteristics in trees are complex traits influenced by multiple genes as well as by environmental factors. They often vary continuously within a population.

In QTL research, scientists use genetic markers to identify the regions of the genome linked to specific traits. Genetic markers are specific DNA sequences known to be located on particular chromosomes. By analysing their inheritance patterns in different individuals or populations, researchers can identify the genomic regions associated with variations in quantitative traits (Du *et al*., 2016). QTL mapping studies are conducted through controlled crosses or by analysing natural populations using techniques such as genetic linkage mapping and association mapping.

When QTLs are identified and mapped they can provide valuable information for tree-breeding programmes. Breeders can use the information to select trees with desired traits, leading to the development of improved germplasm that exhibits qualities such as faster growth, better wood quality and increased resistance to diseases and environmental stressors (Hall, Hallingbäck and Wu, 2016). According to Grattapaglia (2022), MAS has been proposed as a means for accelerating tree breeding by using DNA markers for early selection based on desired traits. Moreover, understanding the genetic basis of quantitative traits in trees could provide insights into the adaptation and evolution of tree species in changing environments (Holliday *et al*., 2017). The effectiveness of MAS in forest trees has been debated, however, and limitations have been identified. The reliance on "major effect" QTLs has proved misleading, resulting in wasted resources. Additionally, forest tree populations exhibit distinct genetic and reproductive dynamics (e.g. longer generation times, higher genetic diversity and complex mating systems) compared with annual crops, which affects the applicability of MAS.

Twenty-three countries reported using MAS for two main purposes – aiding tree-breeding programmes, and evaluating genetic and species diversity within their gene pools. Although some country reports did not specify the exact purpose for which MAS was being used, its utility in improving breeding and knowledge of genetic diversity is evident, suggesting potential for broader application in breeding and conservation programmes. The most common markers referred to in country reports are SSR (simple sequence repeats), AFLP (amplified fragment length polymorphism), DArT (diversity array technology) and SNP (single nucleotide polymorphism). There have also been advances in transcriptome sequencing, the design of specific markers, and the selection of candidate genes for the most important native species. For example, the first reference transcriptomes for six *Dalbergia* species were developed using high-throughput RNA sequencing technologies. In a comparative analysis of *Dalbergia cochinchinensis* and *D. oliveri*, more genes underwent positive selection in *D. oliveri*, which is consistent with its broader ecological niche and higher genetic diversity, illustrating how transcriptome sequencing can aid evolutionary research and conservation efforts (Hung *et al*., 2020).

In the genetic evaluation of European larch (*Larix decidua*) in varied climatic regions (Lstibůrek *et al*., 2020), microsatellite markers were crucial for marker-based pedigree reconstruction. This approach enables the identification of trees with broad adaptability and high productivity, offering a resource-efficient alternative to traditional breeding programmes. The study highlighted the potential of *in situ* genetic evaluation to support sustainable forest management and reforestation in changing environmental conditions (Lstibůrek *et al.*, 2020).

Domínguez *et al.* (2022) used both chloroplast and nuclear DNA markers, including microsatellites Ulm 2 and UR 141, to study DED resistance in *Ulmus minor* and to profile the genetic characteristics of resistant genotypes. These markers were key in establishing genetic barcodes for resistant cultivars by ensuring precise identification and traceability. The study showed that resistance to DED is influenced moderately by genetic factors, suggesting that selective breeding can be an effective tool for enhancing resistance. Genetic diversity can be maintained by incorporating both resistant and susceptible genotypes into breeding programmes, increasing the likelihood of producing offspring with improved resistance. This MAS approach is a valuable strategy for managing DED in elm populations by promoting long-term resilience and disease control (Domínguez *et al.*, 2022).

Oaks (*Quercus* spp.) are targeted by most advanced QTL research. This research typically involves identifying and mapping the genetic loci associated with complex traits such as leaf morphology, bud burst, and disease and drought resistance. Several studies have focused on the genetic basis of these traits in oak species. By identifying and mapping QTLs associated with these traits, scientists have enhanced understanding of genetic diversity in oak species and advanced breeding programmes (Scotti-Saintagne *et al.*, 2004; Casasoli *et al.*, 2006; Brendel *et al.*, 2008; Gailing *et al.*, 2013; Kapoor *et al.*, 2023). QTL studies have also contributed to knowledge on the complex genetic architecture of underlying traits in oaks related to ecological interactions. For example, researchers investigating traits related to oak–pest fungi interactions (Bartholomé *et al.*, 2020) found the presence of exapted resistance to *Erysiphe alphitoides* and *Phytophthora cinnamomi* in pedunculate oak (*Quercus robur*). Although QTL research in oaks continues to evolve (Silva *et al.*, 2020; Fu *et al.*, 2022), the application of its results to forest management and FGR conservation is expected to increase.

Genomic tools

SoW-FGR1 noted that the use of genomic approaches is increasing in FGR research, particularly for model species and economically important species, but that the use of genomic tools was still limited in many countries and the high cost of these technologies is a major barrier to adoption (FAO, 2014a). SoW-FGR1 did not provide information on the number of countries reporting the use of genomic tools.

For the present report, 15 countries – mainly in Asia, Europe and North America – reported the use of genomic technologies, including GWAS and WGS, and other "-omic" methodologies (e.g. advanced tools for studying biological molecules such as DNA, RNA, proteins and metabolites to understand organisms at a molecular level; see Horgan and Kenny, 2011) in their breeding programmes. The cost of the next-generation sequencing needed for WGS and GWAS has been declining since 2014 (Wetterstrand, 2020), making these technologies more accessible to forestry research, including for species beyond breeding programmes. The technologies are used primarily for research and have not been adopted widely for commercial applications.

Genomic selection uses genomic information to predict the performance of trees. By analysing the entire genome of a tree, researchers can estimate its breeding value, enabling the selection of superior trees for traits such as disease resistance, growth rate and wood quality (Grattapaglia *et al.*, 2018). The use of genomic tools in breeding programmes offers new possibilities for addressing complex challenges such as pathogen evolution and climate change (Sniezko and Nelson, 2022), thus supporting sustainable forest management. It is useful, therefore, to combine traditional breeding methods with advanced genomic technologies. This integration helps maintain the resilience and genetic diversity of breeding populations and thereby enable those populations to better cope with evolving diseases and environmental stressors.

WGS in trees is a revolutionary scientific approach that decodes the entire genetic blueprint of tree species. By unravelling intricate DNA sequences, scientists gain insights into traits such as disease resistance, growth patterns and adaptation. Comparative genomics enables the study of evolutionary relationships between tree species to illuminate their genetic history. In conservation, WGS aids efforts to conserve endangered trees by increasing understanding of their genetic diversity. WGS also fuels tree-breeding initiatives by equipping scientists with genetic data that can be used to selectively breed trees for desirable traits. WGS can help identify genetic variations crucial for climate adaptation, and genomic repositories store this wealth of information and promote global collaboration among researchers (Box 10). WGS stands at the forefront of scientific discovery, offering a nuanced understanding of trees and empowering conservation and forestry practices worldwide (Isik, 2014).

Genomic tools have accelerated breeding programmes in various tree species. For example, the use of GWAS and genomic prediction in European ash (*Fraxinus excelsior*) facilitated the identification of SNPs associated with ash dieback resistance, thereby enabling the selection of resistant individuals and enhancing breeding efficiency (Stocks *et al.*, 2019). In Japanese larch (*Larix kaempferi*), RNA sequencing was employed to identify differentially expressed genes in

BOX 10

The TreeGenes database – global cooperation in the field of biodiversity informatics

The TreeGenes database integrates valuable genetic data and whole-genome sequencing data from trees and makes the data more accessible. It provides specialized informatics tools crafted to efficiently manage the large volume of information produced by high-throughput genomics projects concerning forest trees. These tools encompass sample collection through to downstream analysis. TreeGenes systematically curates genomic and phenomic data encompassing 2 392 species in 340 genera. The data linked to each species are sourced from the literature, the NCBI GenBank and PLAZA and include contributions received directly from users. There is also a TreeGenes "colleague directory", which offers a comprehensive profile view of engaged researchers, breeders, foresters and other affiliated members in the community. The existing directory comprises 1 417 users from 748 organizations in 90 countries. An active user account grants access to analytical pipelines and offers the ability to submit data directly to TreeGenes (Falk *et al.*, 2019). The wealth of information accumulated in this online repository has the potential to enhance breeding practices.

Sources: **Falk, T., Herndon, N., Grau, E., Buehler, S., Richter, P., Zaman, S., Baker, E.M., *et al.*** 2018. Growing and cultivating the forest genomics database, *TreeGenes*. Database (Oxford), Jan 1: 1–11. Doi: 10.1093/database/baz043 response to *Phytophthora ramorum* infection, thus enabling the selection of disease-resistant genotypes based on their gene-expression profiles (Dun *et al.*, 2022). Genomic selection has been integrated into tree-breeding programmes to predict and enhance growth and wood-quality traits, significantly reducing the length of breeding cycles and increasing the accuracy of selection of superior genotypes (Grattapaglia, 2022). For example, genomic selection has improved *Eucalyptus* breeding programmes by leveraging genomic data to predict breeding values, thereby facilitating the selection of high-performing genotypes and enhancing genetic gains (Haristoy *et al.*, 2023). Genomic tools are not only streamlining the breeding process, they are also providing a more comprehensive understanding of the genetic architecture of complex traits, leading to more targeted and effective breeding strategies across species.

GWAS can be used to find genes responsible for many phenotypic traits in plants by testing the association between SNPs and target attributes. GWAS investigations have been undertaken in about 15 major tree species, including in *Cryptomeria*, *Eucalyptus*, *Populus*, *Picea, Pinus* and *Sequoiadendron*. The target traits for marker–trait association include wood properties, drought and other abiotic stresses, photosynthesis, growth, disease resistance and fruit quality and yield (Ashwath *et al.*, 2023). GWAS offers swifter and more cost-effective outcomes than traditional QTL-directed research because it does not require bi-parental crossings or progeny screening. Its broader applicability across diverse germplasm, higher-resolution maps through linkage disequilibrium consideration, and enhanced validation capabilities for identified QTLs distinguish it from QTL mapping methodologies (Ashwath *et al.*, 2023).

Building on the integration of traditional breeding and genomic technologies, Nelson (2023) highlighted the synergistic potential of combining conventional breeding methods with genetic engineering to enhance forest resilience and productivity. Nelson (2023) noted that, although traditional breeding has been essential for improving traits such as growth and disease resistance, genetic engineering provides precise tools for addressing specific challenges that conventional methods alone cannot overcome. A notable example is the restoration of the American chestnut (*Castanea dentata*), for which genetic engineering has been employed to introduce blight resistance directly into the species.

Genetic modification

GM in trees involves the deliberate alteration of a tree's genetic makeup to introduce heritable changes, often achieved by inserting, deleting or modifying specific genes or introducing foreign DNA. The aim is to enhance traits such as disease resistance, growth rate and climate-change adaptation (FAO, 2010b). SoW-FGR1 noted that, although GM has the potential to improve the productivity and sustainability of forest plantations, there are concerns about the potential risks and negative impacts of GM on biodiversity and ecosystem services (FAO, 2014a). SoW-FGR1 did not provide information on how many countries reported using GM trees or the extent of such use but noted that the use of GM in forestry is still limited and there was a need for more research and dialogue on the benefits and risks of GM in the forest sector.

Genetically modified transformants have been developed for more than 30 species of forest trees, including *Betula*, *Castanea*, *Eucalyptus*, *Juglans*, *Populus*, *Quercus* and *Robinia* (Chang *et al.*, 2018). China was the first country to release transgenic trees for commercial use, when insect-resistant poplar trees containing a modified *Cry1Ac* toxin gene from *Bacillus thuringiensis* (Bt) was approved for planting in 2002 (see Chang *et al.*, 2018). By 2015, approximately 543 ha of Bt poplar had been planted in China (Chang *et al.*, 2018). In Brazil, GM eucalypts were also approved for planting in 2015 (Nature Biotechnology News, 2015). A frost-tolerant transgenic eucalyptus hybrid (*Eucalyptus grandis* × *Eucalyptus urophylla*) and genetically modified loblolly pine (*Pinus taeda*) engineered for increased wood density are undergoing the deregulation process in the United States of America and are expected to be released soon for commercial use (Ahuja, 2021).

By modifying gene expression related to lignin, cellulose and hemicellulose biosynthesis, researchers have demonstrated the potential to improve saccharification efficiency, which is crucial for biofuel production in poplars (Bryant *et al*., 2020). The impacts of genetic engineering on cell-wall properties are complex and not fully predictable, however, necessitating further research to optimize the biological conversion of transgenic poplar into biofuels. This work underscores the importance of understanding the intricate relationships between cell-wall components and biofuel production efficiency (Bryant *et al*., 2020).

Public and social considerations around the use of genetically modified trees are multifaceted, with implications spanning ecological, cultural and ethical dimensions. In Brazil, the potential environmental risks and the corporate monopolization of genetic resources were debated in conjunction with the approval process for genetically modified eucalypts (Nature Biotechnology News, 2015). In the United Kingdom of Great Britain and Northern Ireland, efforts to tackle ash dieback caused by the fungal pathogen *Hymenoscyphus fraxineus* illustrate the complexity of public attitudes toward genetic interventions (Jepson and Arakelyan, 2017). Genomic techniques, which offer solutions for developing disease-resistant trees, are considered more acceptable when applied in urban or plantation settings than in natural woodlands (Jepson and Arakelyan, 2017), reflecting broader societal concerns about the natural environment. There is strong anti-GM sentiment in the United Kingdom of Great Britain and Northern Ireland but also a pragmatic attitude towards GM if well justified and necessary (Jepson and Arakelyan, 2017). An international study found growing acceptance of GM among younger urban residents, who tend to view it as a practical tool for disease management (Kazana *et al*., 2015). Thus, the public perception of genetically modified trees may be contingent on the benefits outweighing the risks and can be favourable towards GM when seen as necessary to protect biodiversity.

Gene editing

Gene editing is a new, precise method for manipulating genes. GM often involves the insertion of foreign DNA, but gene editing allows targeted alterations to specific genes within an organism's existing genetic code (FAO, 2022d). This targeted approach has at least two advantages: it allows highly specific changes, potentially minimizing unintended effects on other parts of the genome; and, in some cases, it can be faster than traditional methods dealing with GM.

The application of gene editing to trees is in its early stages. It has potential for introducing or enhancing specific traits without traditional breeding methods (Ahmar *et al*., 2021). CRISPR-Cas9 technology ("clustered regularly interspaced short palindromic repeats and CRISPR-associated protein 9"), is a revolutionary gene-editing tool used widely in various organisms. This technology makes precise modifications to an organism's DNA, enabling targeted changes in specific genes. CRISPR-Cas9 is being used in China in *in vitro* studies of various traits associated with abiotic stress tolerance and resistance in tree species used in agroforestry systems. Several studies have used fast-growing tree species as model organisms to determine gene functions and explore the potential applications of research findings in breeding acceleration. Species that have been targeted and investigated include *Populus tomentosa* (Fan *et al*., 2015), *P. tremula x alba* (Jiang *et al*., 2017) and *P. tremula x tremuloides* (Wan *et al.*, 2017; Yang *et al*., 2017; Xu *et al*., 2017; Shen *et al*., 2018).

In Japan, Nishiguchi *et al.* (2023) applied CRISPR-Cas9 genome editing technology to disrupt the CjACOS5 gene in sugi trees (*Cryptomeria japonica*), leading to the development of pollen-free trees. This advancement holds promise for mitigating the impacts of pollen allergy syndrome, particularly Japanese cedar pollinosis, which poses a significant health challenge in Japan. Importantly, Nishiguchi *et al.* (2023) underscored the broader spectrum of objectives pursued in gene editing research in the forest sector, extending beyond wood production to include environmental and public-health considerations.

Although the potential of CRISPR-Cas9 in tree breeding is promising, ongoing debate surrounds the ethical implications and potential environmental concerns associated with it (FAO, 2022d). Given its minimal use of foreign DNA, gene editing may fall under non-GM regulatory frameworks. Occasionally, however, gene editing can involve the incorporation of foreign genetic sequences and, as with any scientific technique, the possibility of unintended consequences remains. Careful consideration of potential ecological impacts and suitable regulatory frameworks is essential as the use of this technology continues in tree breeding.

9.4 Conclusions

Tree improvement and breeding programmes are operational in all regions, albeit at different levels of intensity and investment. Tree-breeding programmes focus on a relatively small number of economically important tree species and, for most of these, have not advanced beyond the first generation of selection. In their reports, many countries highlighted the challenges their tree-breeding programmes face, including the need for tailored approaches that align with their specific ecological and economic contexts. Capacity building and research infrastructure development were identified as pressing needs to advance these programmes.

Despite these limitations, notable advances have been made in the integration of new technologies, particularly in countries with well-established, long-running breeding programmes. Many countries reported using MAS and genomic tools for accelerating tree-breeding programmes and enhancing FGR management. Although the adoption of these technologies has increased over the last decade, they are mostly confined to research and more advanced breeding systems.

The use of genetically modified trees in forestry is still limited and driven by wood production, although examples exist of the use of GM for developing disease-resistant trees for restoration. The application of gene editing in trees is in its early stages, although several studies have been conducted to determine gene functions in trees and to explore the potential of this technology for accelerating tree improvement and breeding.

Chapter 10

Management of forest genetic resources

10.1 Introduction

Archaeological evidence shows that people started to actively manipulate forests at least 45 000 years ago (Roberts *et al.,* 2017), and human activities have continued to affect forests worldwide since then. In 2020, agricultural lands (croplands and permanent meadows and pastures) were the predominant land-use type, accounting for 36 percent (4.74 billion ha) of the global land area, and forest accounted for 31 percent (4.06 billion ha) (FAO, 2022e). From an evolutionary point of view, deforestation and forest fragmentation, the transfer of germplasm beyond species' native ranges, and selective harvesting have been the most significant anthropogenic impacts on forests (Geburek and Myking, 2018).

Ninety-three percent of the world's forests are naturally regenerating (see Chapter 2), and the long-term management of these forests is crucial for safeguarding FGR. SoW-FGR1 stressed the role of sustainable forest management in maintaining biodiversity while enabling the use of forests for various products and services (FAO, 2014a). Sustainable forest management is a globally accepted concept for developing and implementing policies and practices that maintain and enhance the economic, social and environmental benefits of forests (Box 11). Planted forests, woodlands and agroforestry systems also play important roles in FGR management and use.

All conservation and production systems containing trees and other woody plants contribute to a greater or lesser extent to the management of FGR (FAO, 2014a). Some, however, such as production systems based on high-grading (that is, selective cutting) or a few clones, can be detrimental to genetic diversity.

The *in situ* conservation of FGR in production and protected forests forms the backbone of FGR management, supported by the *circa situm* conservation of remnant or planted trees in farmlands and other areas where forests were once found (see Chapter 6); the balance between these elements varies, depending on the country and ecosystem. The *ex situ* conservation of FGR is the other element supporting the use of FGR for establishing new forests and tree-based production systems (see Chapter 7). Ideally, all the elements are brought together by a national FGR strategy that sets objectives for FGR management and through which the integration of FGR into other relevant national policies and strategies is promoted (see Chapter 11).

The implementation of sustainable forest management in the field (i.e. at the level of management units) requires balancing multiple objectives for forests and the application of practices based on science and knowledge of local conditions and traditions. Although it is possible to produce several products and services in individual forest management units (or stands) efficiently, it is difficult to balance all management objectives within a single unit. Therefore, at the landscape level, multiple-use forest management typically creates a mosaic of spatially defined management units, each of which is allocated to one or more uses to

BOX 11

The concept of sustainable forest management

In Resolution 62/98 (UN, 2007), the United Nations General Assembly recognized that forests and trees outside forests provide multiple economic, social and environmental benefits and emphasized that sustainable forest management contributes significantly to sustainable development and poverty eradication. It further recognized sustainable forest management as a dynamic and evolving concept that is intended to maintain and enhance the economic, social and environmental values of all types of forests, for the benefit of present and future generations. Sustainable forest management, as defined by Resolution 62/98, consists of seven elements: (1) extent of forest resources; (2) forest biological diversity; (3) forest health and vitality; (4) productive functions of forest resources; (5) protective functions of forest resources; (6) socioeconomic functions of forests; and (7) legal, policy and institutional framework.

which it is most suited (Sabogal *et al.,* 2013), such as wood production, the extraction of non-wood forest products (including food and fodder production), biodiversity conservation, and erosion control. Multiple uses are also challenging to balance across forest biomes.

The genetic impacts of forest management practices depend on the silvicultural system applied, stand structure, and species' demography, biological attributes and ecology (Ratnam *et al.,* 2014). Ratnam *et al.* (2014) stressed the importance of taking the population size, reproductive biology and growth rate of a species into account in forest management to ensure that genetic diversity and evolutionary processes are maintained in forests.

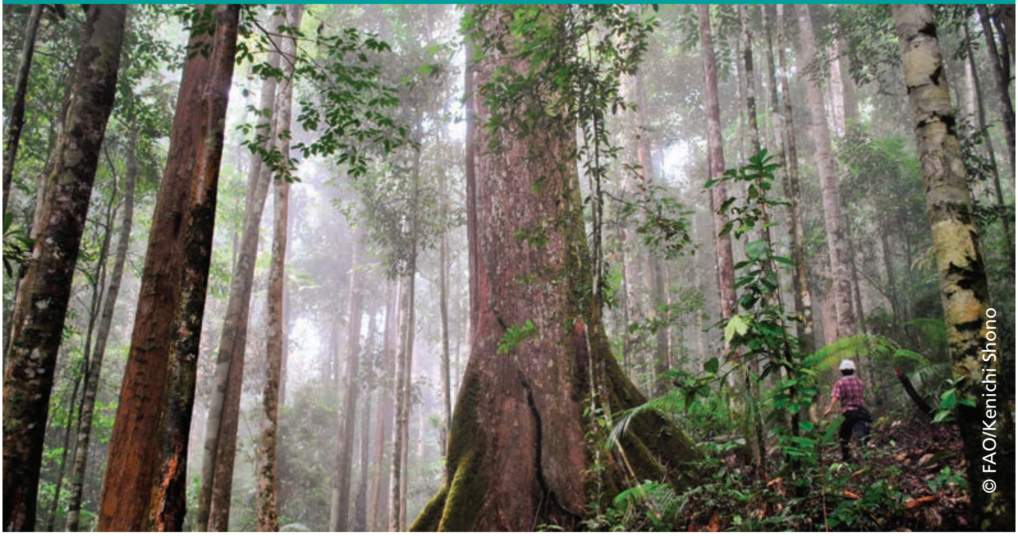
In its priority areas 2 and 3, the Global Plan of Action recommended many actions for improving FGR management (FAO, 2014b). This chapter focuses on genetic aspects of managing natural and planted forests, discusses the key drivers of change and trends in the forest sector affecting FGR and their management, and summarizes needs, challenges and opportunities for improving FGR management, as identified by countries in their reports.

10.2 Genetic considerations in forest management

Decisions by forest managers and farmers influence the success of managing natural and planted forests, woodlands and agroforestry systems. A crucial phase in the forest management decision-making process is the selection of regeneration method because this sets the long-term path for subsequent silvicultural practices for directing stand development and meeting management objectives. Regeneration – whether natural or artificial – always involves the use of FGR. Natural regeneration relies on germplasm that is already present on a given site, and artificial regeneration typically requires transferring seeds or seedlings from other locations to the site.

Although most of the world's forests are naturally regenerating, it does not mean that FGR have developed without human influence or that the FGR found at a particular site are autochthonous (i.e. indigenous to that site). Almost all forests worldwide, including seemingly pristine tropical rainforests, have been affected by human use (McNeely, 1994). Past human interventions have also extended the original distribution of many trees, such as baobab (*Adansonia* spp.) and apple-ring acacia

A forest concession in Indonesia



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(*Faidherbia albida*) in Africa (Stalker, Warburton and Harlan, 2021) and chestnut (*Castanea sativa*) in Europe (Conedera *et al.,* 2004) into new areas now considered part their "natural" distribution.

Forest management has traditionally built on the assumption that, in the absence of human influence, frequent small-scale disturbances, such as gaps created by treefalls, drive succession and shape the species composition and structure of forest biomes (e.g. Oliver and Larson, 1996; Bruenig, 2017). Recent studies have shown, however, that infrequent large-scale disturbances also play important roles in boreal, temperate and tropical forests (Druckenbrod *et al.,* 2019; Martin, Morin and Fenton, 2019; Vlam *et al.,* 2017). For example, ecological studies and archaeological evidence have shown that the tropical forests in Mesoamerica have been subject to not only treefall disturbances but also infrequent large-scale disturbances caused by landslides, flooding, erosion, earthquakes and hurricanes, which, in turn, are driven by climate and geology (Fernandez-Vega, Covey and Ashton, 2017).

Forests have also been exposed to disturbances for a long time. Over the past 2.6 million years (the Quaternary Period), the Earth has experienced drastic climatic changes, including glaciations, and most present-day living organisms, including trees, retain genetic and other legacies from these (Hewitt, 2000; Svenning *et al.,* 2015). The distributions of tree and other woody plant species have not been static; rather, they have dynamically contracted, expanded and shifted in response to climatic change, and this has affected the existing diversity of trees worldwide (Xu *et al.,* 2023). Moreover, past climatic changes have shaped gene pools of boreal and temperate tree species (Petit *et al.,* 2003; Milesi *et al.,* 2024) and tropical tree species (Duminil *et al.,* 2015; Demenou, Piñeiro and Hardy, 2016). The genetic make-up of the world's forests has thus been shaped by people and disturbances at different scales over millennia. This should be considered in FGR management, such as the selection of regeneration method.

The country submissions for the present report indicated that genetic aspects are considered more frequently in the management of planted forests than of natural forests. This is understandable because the selection of species and appropriate provenance for a given site is a crucial step in the establishment of planted

Planted forests in China

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forests. Moreover, the importance of genetic aspects is typically emphasized in guidelines for deploying forest reproductive material but have received less attention in management guidelines for natural forests. Some country reports noted that this results from a tendency among forest managers and policymakers to underestimate the importance of genetic aspects. It was also noted that forest managers and policymakers sometimes assume that, by following general guidelines for sustainable forest management, FGR are also managed adequately.

Despite this, some countries indicated that awareness of genetic aspects is increasing among forest managers: for example, Canada's report noted that the country's forest industry has paid increasing attention to genetic diversity in recent years in the context of both planted and natural forests. This may be due to growing recognition that genetic diversity is essential for adaptation to climate change and coping with pests and diseases.

Several countries stressed the importance of mechanisms at the national level to oversee the production, testing and documentation of forest reproductive material to ensure that seeds and other reproductive material are obtained from registered sources and that high-quality, genetically diverse reproductive material is available for the establishment of planted forests. In some countries, especially in Europe, the marketing of forest reproductive material is regulated by law and the production of the material is overseen by government agencies. In other countries, the use of forest reproductive material is guided not by law but by science-based guidelines, and the final decision on use is taken by the forest owner or manager; a designated authority certifies documentation of the origin and genetic quality of material to enable forest owners and managers and other end-users to make informed decisions when purchasing material. In addition to such guidelines, Germany and Ireland reported that they have grant schemes that provide financial incentives to private forest owners to follow provenance recommendations.

A lack of the above-described mechanism typically limits the availability of forest reproductive material and increases the risk that tree-planting efforts will fail because of the use of poorly documented and low-quality material. In its country report, Guinea reported that although the country has 15 reforestation schemes, no mechanism is in place at the national level for overseeing the production of forest reproductive material. As a result, the material used for reforestation is commonly sourced from undocumented and often degraded tree populations in the country and occasionally from seed traders outside the country.

Some countries with well-functioning mechanisms for the production and documentation of forest reproductive material are taking additional action. The 2020 forest strategy of the Republic of Korea recognizes the importance of FGR management and especially the availability of improved germplasm for wood production and climate-change mitigation. As part of its forest strategy, the country is increasing the production of forest reproductive material through the establishment of advanced-generation seed orchards to replace ageing orchards and by enhancing the quality of its registered seed stands.

Genetic information is also important beyond the stand establishment phase, and forest managers would benefit from connecting this information to the long-term performance of the deployed reproductive material in operational forestry. Norway, for example, reported that all seedlings delivered from nurseries are part of a national reference system that enables forest owners and managers to check which seed source was used to raise the planting stock they purchase. The deployment sites of a given material are not tracked systematically, however, and there is a lack of awareness among forest owners of the importance of retaining planting-stock reference numbers for future monitoring purposes.

The country reports showed that more species and genetic diversity is being sought for planted forests. The Kingdom of the Netherlands reported that more broadleaved tree species have been planted in the last decade, with forest management aiming to increase the diversity of tree species for biodiversity conservation and to improve forest resilience. Brazil noted that planted forests of introduced eucalypts and pines are increasingly being diversified with more clones and families to avoid abiotic and biotic problems due to a lack of diversity.

Countries are also considering genetic aspects in the restoration of degraded forest ecosystems. In Argentina, genetic zones (i.e. genetically homogeneous areas within which forest reproductive material can be transferred without altering the genetic structure of tree populations) have been developed for several native tree species, such as *Austrocedrus chilensis* (Pastorino, Aparicio and Azpilicueta, 2015) and four *Nothofagus* species (Azpilicueta *et al.,* 2016; Soliani *et al*., 2017; Mattera *et al*., 2020). Moreover, a genetic rescue programme has been developed for *Salix humboldtiana*, the country's only native willow species, which is threatened by hybridization with introduced willows that have become naturalized in its native range (Gallo *et al.,* 2020).

Along with an overall tendency to consider genetic aspects more in the management of planted forests, the country reports provided many examples of how genetic aspects are also taken into account in natural forests. In Australia, the management of natural forests involves the consideration of genetic aspects for both conservation and wood production. The country reported that genetic information (e.g. the number of tree populations, their sizes, the extent of fragmentation and measured genetic diversity, the occurrence of hybridization and possible fecundity issues) is used in the management of some threatened tree species, although this information is available only for a relatively small number of tree species. The maintenance of genetic diversity as a management goal is also recognized in Australia's legislation, regulations and codes of practice for natural forest management, with which private-sector forest managers and government agencies should comply.

Genetic aspects have received attention in several European countries. In France, the National Office for Forests was tasked in 2011 with providing guidelines and technical recommendations for the management of FGR in public forests. Germany's 2020 forest strategy refers to the maintenance of forest genetic diversity as part of sustainable forest management, and efforts have been made to integrate FGR conservation into routine forestry practices to safeguard the genetic potential of forests. The Kingdom of the Netherlands reported that the management of remaining rare autochthonous tree populations in semi-natural forests is gaining more attention.

Management plans are a vital tool for practical forest management, and the incorporation of genetic aspects into these plans would help meet sustainability criteria. In El Salvador, forest owners are encouraged to favour the retention of trees with good phenotypes when developing management plans for naturally regenerating forests. Serbia noted the importance of taking genetic aspects more into account in forest management planning and called for improved methodologies for collecting data on FGR as part of regular forest inventories and for the use of these data in the planning process. Although the global coverage of forests with long-term management plans has increased over the last 30 years, such plans have mostly been developed for boreal and temperate forests, and only 21 percent of tropical forests were subject to such plans in 2020 (Shono and Jonsson, 2022). No detailed data are available at the global level on the extent to which genetic aspects are included in forest management plans.

10.3 Drivers of change affecting the management of forest genetic resources

SoW-FGR1 reviewed the major drivers of change affecting forests and FGR management, which included the conversion of forests to agriculture, climate change, the unsustainable harvesting and use of forests, outbreaks of insect pests and pathogens, invasive species, browsing by livestock and wildlife, and genetic pollution (FAO, 2014a). The country submissions for the present report indicated that these major drivers of change have remained largely the same.

Deforestation and forest degradation

The rate of global deforestation has slowed in recent decades, but forests are still being cleared, especially in Africa, Asia and Latin America and the Caribbean (see Chapter 2). Forests continue to be degraded, too, due mainly to woodfuel harvesting and charcoal production in Africa and wood extraction in Asia and Latin America and the Caribbean. Consequently, the erosion of FGR continues, especially in tropical forests, where most deforestation and forest degradation is taking place.

In its submission, Brazil reported continuing threats to FGR due to deforestation and forest degradation. Despite various measures to halt deforestation and promote sustainable forest management, the country noted that natural forests are still being lost and degraded, representing a significant challenge for FGR conservation. Most deforestation is taking place in the Amazon region, driven largely by illegal activities. In Brazil, wood can legally be harvested in the Amazon, Caatinga, Cerrado and Pantanal biomes. In the Amazon, the recommended selective management system involves a 25–35 year cutting cycle with a maximum harvesting intensity of 30 m^3 per ha and technical standards to promote the natural regeneration of target tree species. Brazil reported challenges in curbing illegal activities and enforcing sustainable silvicultural practices in its vast forest area.

Argentina, Sri Lanka and Thailand also reported that deforestation and forest degradation represent threats to FGR, although current rates of both have declined.

In Argentina, the enactment in 2007 of Law No. 26.331 designed to reduce deforestation and promote sustainable natural forest management has helped slow deforestation in recent years. It also created a trust fund – based on payments for ecosystem services – for this purpose and established enforcement authorities with a mandate to monitor natural forests, in coordination with the provinces. Nevertheless, deforestation continues, with the Parque Chaqueño region accounting for nearly 90 percent of deforestation between 2007 and 2018. Despite challenges in implementation, Argentina reported that the law has proved useful for the conservation of FGR and in increasing public awareness of the importance of forests and FGR.

According to the country report submitted by Sri Lanka, natural-forest management in the country is improving, but past deforestation continues to threaten FGR. A challenge for some endemic tree species, such as *Polyspora dassanayakei*, is that populations have been reduced to small numbers of trees, which often occur outside natural forests and protected areas.

Deforestation has decreased significantly in the last decade in Thailand due to extension efforts with forest dwellers and strict law enforcement measures, with 1 822 illegal logging and deforestation cases reported in 2021, down from 7 385 cases in 2014. Thailand indicated that illegal logging is targeting high-value protected timber species, such as rosewoods (*Dalbergia* spp.), and fire is a main cause of forest degradation in seasonally dry forest ecosystems.

Forest conversion to other land uses is also a threat to FGR in the temperate and boreal zones. Germany, for example, reported that FGR are put at risk by the clearing and fragmentation of forests for the construction of commercial and residential areas and other infrastructure.

Climate change

It is likely that global warming will exceed 1.5 °C during the twenty-first century, bringing more widespread and pronounced weather extremes and creating cascading climatic and non-climatic risks that are more difficult to manage (IPCC, 2023). Climate change, therefore, will continue to affect FGR long into the future. Aitken *et al.* (2008) identified three possible pathways for populations of trees and other woody plant species: (1) they may survive in their current locations by adapting genetically; (2) they may migrate to new locations with favourable climatic conditions; or (3) they may be extirpated (i.e. experience local extinctions). The required rates of adaptation and migration to enable populations to respond to climate change are likely to outpace historic rates (Aitken *et al.,* 2008); some populations, therefore, will probably experience local extinction (Alfaro *et al.,* 2014). This may already be happening in some forest ecosystems: for example, Davis *et al*. (2019) found that climatic conditions in the western United States of America in the last 20 years have become increasingly unsuitable for the natural regeneration of low-elevation ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*).

Alfaro *et al.* (2014) recommended that FGR management under climate change should focus on maintaining large, genetically diverse populations and assisted migration – that is, the human-mediated transfer of forest reproductive material from current locations to new sites for which climate models predict favourable conditions in the future. Because these new sites are typically found beyond species' current distributions, the ecological risks and philosophy of assisted migration have been debated (see Chapter 8). Nevertheless, scientific evidence supports the necessity and urgency of assisted migration to facilitate the adaptation of tree species (e.g. Aitken and Bemmels, 2015; Conroy *et al.,* 2019; Standurf, Ivetić and Dumroese, 2024). The report submitted by the United States of America noted that climate change is expected to outpace the ability of trees to adapt or migrate without assistance and that, therefore, assisted migration is a key strategy for alleviating the impacts of climate change on FGR. The country report indicated that existing common garden studies are being revisited, and new ones established, to help in making informed seed-transfer decisions for assisted migration.

Australia reported ongoing debate on assisted migration and renewed efforts to re-analyse existing provenance trials and to establish new ones to obtain the information needed for managing FGR effectively as the climate changes. Widely distributed eucalypts such as *Eucalyptus salubris, E. tricarpa* and *E. loxophleba* are expected to cope with climate change, but the adaptive capacity of narrow-range eucalypt species is considered low (Booth *et al.*, 2015). Conserving narrow-range eucalypts and threatened rainforest tree species such as *Fontainea rostrata* is expected to require assisted migration. The southern populations of *F. rostrata* in eastern Australia are likely to persist under climate change, but the genetically less-diverse northern populations should be helped to migrate southwards (Conroy *et al.*, 2019). Australia reported that current FGR management favours species and genotypes that are resistant to or tolerant of warmer and drier conditions and potential increases in the number, spread and severity of pests, diseases and weeds associated with climate change. The country report indicated that assisted migration is needed for both commercial and environmental tree-planting and that securing genetically diverse seed collections can help tree species cope with present and future threats.

Several countries reported that altered fire regimes have damaged large areas of forests and that the increasing frequency and intensity of fires are creating further challenges for FGR management. Fires in southern and eastern Australia were unusually extensive in 2019–2020 after an extended drought. A total of 10.3 million ha of land (of which 8.5 million ha was forest) were burnt in that fire season, with significant impacts on many tree species. For example, 25 percent of the known distribution of *Macadamia jansenii*, an endangered tree species, was burnt. This species' remaining population consists of about 200 individuals; some individuals are coppicing, but the long-term effect of the 2019–2020 fires on the species is yet to be assessed. Prioritization exercises undertaken by the Australian Government identified 486 plant species requiring rapid management interventions, including three tree species – *Eucalyptus gunnii, E. remota* and *Wollemia nobilis*.

In its report, Canada also noted that climate change has brought more-intensive fires in recent years, reporting that more than 7 000 recorded fires burnt nearly 2.3 million ha of forest in 2018. This annual area is close to the 20-year average, and fires are now also occurring in historically unusual places, such as Vancouver Island, which is noted for its temperate rainforests, and in wooded wetlands. Canada experienced fewer fires in 2021 (6 500) but the burnt forest area was higher, at about 4.3 million ha (Natural Resources Canada, 2022). In its country report, Canada indicated that climate change and associated changes in fire regimes and outbreaks of insects and pathogens represent the most significant threats to FGR. Other countries that reported fire as an increasing threat to FGR included Brazil, Croatia, Greece, Lebanon, Portugal, the Republic of Korea, Thailand and the United States of America.

Climate change is likely to also affect FGR by increasing the incidence and facilitating the spread of insect pests and diseases (FAO, 2014a). Studies have confirmed that climate change is rapidly intensifying the impacts of insect pests and diseases in forests and that gaps in the understanding of agent–host interactions are hindering the design and implementation of management interventions (see Simler-Williamson, Rizzo and Cobb, 2019). Climate change is also affecting the insect and fungal communities of trees, both directly (by increasing temperature and lowering precipitation) and indirectly (through host range shifts) (Franić *et al.*, 2023). Disentangling direct and indirect effects is a complex task, however, due to the large number of variables involved (Pureswaran, Roques and Battisti, 2018). Additionally, climate change may enable insect pests and pathogens to survive in new locations to which they are brought by global trade networks (see also below).

A concern in temperate and boreal regions is that temperature and moisture conditions altered by climate change are increasing the overwinter survival of insect pests and pathogens and the growth rates of their populations (Simler-Williamson, Rizzo and Cobb, 2019). For example, spruce bark beetle (*Ips typographus*) in Europe and mountain pine beetle (*Dendroctonus ponderosae*) in North America can produce more than one generation in a single growing season. Moreover, extended periods of moisture in western North America are facilitating the reproduction of *Mycosphaerella pini*, which causes pine needle blight (Simler-Williamson, Rizzo and Cobb, 2019). This fungus is believed to be native to the cloud forests of Central America but has now spread worldwide (FAO, 2009b).

Most (81 percent) countries that made submissions for the present report cited pests and diseases as a problem for FGR management. Insect pests and diseases have ravaged large areas of forests in the last decade, especially in North America. Canada reported that insect pests and pathogens defoliated a total of 15.6 million ha of forests in 2017. The United States of America reported that insect pests and diseases (both native and non-native) were associated with nearly 2.3 million ha of tree mortality in the same year.

Several countries in Europe reported increasing damage by insect pests and diseases. In Sweden, 3–4 million m^3 of growing spruce (*Picea abies)* trees were killed by an outbreak of bark beetle (*Ips typographus*) during the very hot and dry summer of 2018, and the damage was even greater in 2019, at 7 million m^3. Sweden's report noted that pine weevil (*Hylobius abietis*) and several other insect pests are also being favoured by climate change. Pests and diseases damaged nearly 800 000 ha and 270 000 ha of forests in Poland and Ukraine, respectively, in 2019.

Countries in other regions provided less-detailed data on the area of forest damaged by pests and diseases, probably due to less-systematic monitoring compared with Europe and North America. Argentina indicated damage to cedar species (*Cedrela angustifolia, C. balansae* and *C. fissilis*) by mahogany shoot borer (*Hypsipyla grandella*) and efforts to control this pest with low-toxicity chemicals, biocontrol agents and tree improvement. Lebanon reported that climate change has caused recurrent and intense outbreaks of cedar web-spinning sawfly (*Cephalcia tannourinensis*) and pine processionary caterpillar (*Thaumetopoea wilkinsoni*). In Sri Lanka, insect pests such as defoliators, bark beetles and shoot borers have damaged tree plantations.

Invasive species

SoW-FGR1 listed many invasive insects, pathogens and plants that have been identified and reported as major threats to FGR worldwide (FAO, 2014a). Based on the country submissions for the present report, invasive species continue to threaten FGR and cause large-scale economic and ecological damage to forests. Global trade networks are the main pathways for the introduction of invasive species to new areas (Chapman *et al.,* 2017), and their role in the spread of invasive species is unlikely to diminish in the future; climate change is also facilitating the establishment and spread of such species (Gullino *et al.,* 2022).

Although newly introduced insect pests and pathogens have had devastating impacts on forests, some surviving individual trees (with varying degrees of resistance) typically remain in the aftermath of such impacts (Budde *et al.,* 2016). It is often impossible to eradicate invasive species once they have become established in new areas. Therefore, it is important to continue to implement phytosanitary regulations and other measures against invasive species and to monitor their spread. It is also crucial to develop genetic solutions to mitigate the economic and ecological damage and speed up the evolution of tree species so they can co-exist with these antagonist species.

Some invasive insect pests are reported to threaten FGR in various regions. For example, the emerald ash borer (*Agrilus planipennis*), which is native to eastern Asia, has spread to other parts of Asia and to Europe and North America. Ukraine reported that the emerald ash borer was found in the eastern part of the country in 2019 and that damage has since been documented to ash trees (*Fraxinus* spp.). In North America, emerald ash borer has killed hundreds of millions of ash trees since 2002, when it was first documented, and it has spread to six provinces in Canada and 35 states in the United States of America (Emerald Ash Borer Network, undated). Canada reported that the pest has decimated all ash species throughout their ranges in the country. The United States of America reported extensive damage to forest ecosystems in which ash is predominant, as well as to the local communities and forest industries dependent on such forests. As a result, the International Union for Conservation of Nature has listed five North American ash species – white ash (*Fraxinus americana*), black ash (*F. nigra*), green ash (*F. pennsylvanica*), pumpkin ash (*F. profunda*) and blue ash (*F. quadrangulata*) – as critically endangered (IUCN, undated).

Pine wood nematode (*Bursaphelenchus xylophilus*), a native of North America, causes a wilt disease in pines and other conifers. It has spread to Asian and European pine forests, causing widespread tree mortality in China, Japan, the Republic of Korea and Portugal (FAO, 2009b). Japan reported that the socially and economically important pine species *Pinus densiflora*, *P. thumbergii* and *P. luchuensis* are highly susceptible to the pine wood nematode and that continuous control measures are being implemented. Japan indicated that pine wilt disease is attributed to the rapid decline of an endangered pine species, *P. amamiana*, which occurs only on a few islands in the country's southwest. China reported that the pine wood nematode has caused substantial damage to forestry in the country but that prevention and control technology is becoming more successful. In Europe, the spread of the nematode has so far been limited to the maritime pine (*P. pinaster*) forests of Portugal, which reported advances in tree-breeding efforts against pine wilt disease. The nematode is expected to spread to other European countries; Finland indicated that it has developed a contingency plan for it.

Australia reported the continued spread of myrtle rust (Austro*puccinia psidii*), which was first detected in the country in 2010. This pathogen is now present in most Australian states and territories, and at least 358 plant taxa have been observed to be susceptible to it. Australia also reported that forests that are rich in species in the *Myrtaceae* family have been severely damaged by myrtle rust and that the populations of two widespread rainforest tree species, *Rhodamnia rubescens* and *Rhodomyrtus psidioides*, are in rapid local decline due to infection.

In Europe, the invasive pathogen *Hymenoscyphus fraxineus*, which causes ash dieback disease, continues to cause devastating damage to ash trees. Many European countries reported that the pathogen is a major threat to the genetic resources of especially common ash (*Fraxinus excelsior*). Several reporting countries noted ongoing efforts to assess genetic variation in susceptibility to the disease and related tree-breeding efforts.

Other invasive pathogens also continue to increase in impact. Sweden reported an outbreak of a new pathogen, *Diplodia sapinea*, on Scots pine (*Pinus sylvestris*) in 2016. This is a cosmopolitan fungus that causes shoot blight and canker disease on conifer trees worldwide (FAO, 2009b), but its occurrence in Europe was previously limited to the southern part of the continent (e.g. Luchi *et al.,* 2014). It is now expected to become a serious pathogen in northern Europe because of climate change (Brodde *et al.,* 2019).

Only a few countries mentioned invasive plant species in their reports, such as Sri Lanka, which indicated that a range of cacti, herbs, shrubs, trees and vines are considered invasive. The country noted, for example, that mesquite (*Neltuma juliflora*, syn. *Prosopis juliflora*) has become a serious invasive plant that threatens ecosystems in several natural parks, and that prickly pear cactus (*Opuntia tuna*) has hindered the regeneration of coastal vegetation destroyed by the 2004 tsunami. The United States of America reported that Asian bush honeysuckles (*Lonicera* spp.) are a major hinderance to forest regeneration efforts in parts of the country; numerous other invasive plant species, such as musk thistle (*Carduus nutans*), buffelgrass (*Cenchrus ciliaris*), Japanese stiltgrass (*Microstegium vimineum*), seven sisters rose (*Rosa multiflora*) and salt cedar (*Tamarix ramosissima*), are also documented in the country (Poland *et al.,* eds, 2021). Chinese windmill palm (*Trachycarpus fortunei*) is an invasive species in Switzerland's southern forests and is suspected of hindering the natural regeneration of native trees in the country (Tonellotto *et al*., 2022). Eighty terrestrial plant species are considered invasive in Switzerland (FOEN, 2022).

Browsing

SoW-FGR1 reported that browsing by livestock and wildlife is a serious threat to FGR in many parts of the world (FAO, 2014a). In their submissions for the present report, several countries reported that browsing is a continuing challenge to forest management and especially their regeneration. In Japan, the habitat area of wild deer nearly tripled between 1978 and 2018 and almost 70 percent of reported damage by wildlife is attributed to deer. Browsing and damage to stems have increased seedling mortality and reduced tree growth in the country and caused timber losses. Japan also noted that browsing has negatively affected efforts to conserve biodiversity and soil.

Problems related to browsing by wildlife were also reported in Europe and North America. In its report, Germany noted that overabundant game populations in parts of the country pose a major problem to forest management and threaten the conservation of rare tree species. The Kingdom of the Netherlands reported that large populations of ungulates are hampering the natural regeneration of rare autochthonous tree populations and expressed concern about possible losses of genetic diversity in new tree generations. In the eastern United States of America, large populations of white-tailed deer (*Odocoileus virginianus*) are damaging broadleaved tree seedlings, with managers needing to invest in fencing or chemicals to protect seedlings.

Livestock can also threaten FGR. For example, Lebanon reported that grazing by livestock is one of the main threats to existing forests and reforestation efforts. The country has more than 500 000 goats, and oak forests especially are used for grazing.

Unsustainable harvesting

Species that produce high-value timber and/or non-wood products are more likely to be overharvested than those harvested for lower-value products such as fuelwood and charcoal (FAO, 2014a). Unsustainable harvesting can cause genetic erosion and threaten rare and narrowly distributed tree and woody plant species. SoW-FGR1 listed several examples of overharvesting that was hindering the sustainable management of FGR (FAO, 2014a). In submissions for the present report, several countries considered unsustainable harvesting to be a significant threat to FGR, but it is unclear from these submissions whether the threat has decreased or increased in the last decade. Based on country reports, however, it is clear that many species have not recovered from historical overharvesting. The harvesting of non-wood forest products such as honey can have detrimental effects on FGR (Box 12).

Argentina reported the overharvesting of red quebracho (*Schinopsis balansae*), which is valued for timber and for tannins extracted from its wood. High-grading was practised in the Patagonian forests dominated by *Nothofagus* spp. until the 1990s, and this has likely affected the genetic resources of these species; the gene pools of several other tree species, such as *Aspidosperma* spp., *Cedrela* spp., *Cordia* spp. and *Handroanthus* spp., have also been affected by selective and excessive harvesting in past decades. According to the country report, excessive selective logging cycles have progressively caused forest degradation; moreover, following extraction of high-value species, the remaining species have often been harvested to produce fuelwood and charcoal.

Brazil reported that the genetic impoverishment of many tree species and their populations due to past indiscriminate overharvesting is still evident in all forest biomes. Examples include brazilwood (*Paubrasilia echinata*) and Brazilian rosewood (*Dalbergia nigra*), which now only occurs in small fragments of the Atlantic Forest. The Atlantic Forest has many other intensively used tree species, such as aderno (*Astronium concinnum*), Spanish cedar (*Cedrela odorata*), canarywood (*Centrolobium microchaete*) and peroba (*Paratecoma peroba*). Brazil also reported that

BOX 12
Impacts of honey-gathering on tree populations in the Niassa Reserve, Mozambique

The Miombo woodlands cover about 2.7 million km^2 in southern Africa and provide woodfuel and non-wood products for millions of rural and urban people in Angola, the Democratic Republic of the Congo, Malawi, Mozambique, the United Republic of Tanzania, Zambia and Zimbabwe (Gumbo *et al*., 2018). The Niassa Reserve in northern Mozambique covers 42 000 km^2 of some of the least-disturbed Miombo woodlands, protecting wildlife and providing a home for more than 40 000 people (see Snook *et al.*, 2015). Honey is a major non-wood product in the reserve, and it provides local communities with cash income in addition to food (Gumbo *et al.,* 2018). Collection practices are often detrimental to the long-term sustainability of honey-gathering, however, and may also negatively affect forest genetic resources (FGR) (Snook *et al.,* 2015). Trees are often felled to access wild beehives in stem cavities or debarked to obtain materials for the construction of artificial beehives. Resulting tree mortality and treefelling for other purposes not only destroys bee colonies, it also reduces the nectar resources on which the bees depend.

To understand and contribute to addressing these problems, Bioversity International and partners investigated the impact of honey-gathering on tree populations in the Niassa Reserve and looked for solutions to improve FGR management and enable the long-term sustainability of the practice. Cutting trees to gather wild honey from cavity hives was found to be the principal source of tree mortality near villages – while simultaneously destroying honeybee colonies (Snook *et al.,* 2015). Additionally, fires lit to tranquilize bees while harvesting honey often cause wildfires, with negative impacts on tree regeneration and other plant and animal species (Snook *et al.,* 2015). In one location (Lizongole, Mecula District), 12 of the 25 tree species present were affected by honey-related activities and, depending on the abundance of a given species, 3–50 percent of all trees died due to honey-gathering (Ribeiro *et al.,* 2019). Because felling and debarking for honey

demand is growing for seeds of native species to be used in forest restoration and to produce wood and non-wood products.

Thailand offers another example of species' slow recovery from historical overharvesting. In 1987, the country introduced a licence fee for the harvesting of rattan (*Calamus* spp., *Korthalsia* spp., *Myrialepis* spp., *Plectocomia* spp. and *Plectocomiopsis* spp.) in natural forests and banned the export of unprocessed canes. Local people also harvest some rattan species for food, and this practice has been allowed to continue without licences. The country's rattan resources are depleted, although the cultivation of rattan on private lands has become more popular despite the challenges involved. Thailand continues to have a significant rattan industry, based largely on canes imported mostly from Indonesia.

10.4 Needs, challenges and opportunities for improving the management of forest genetic resources

To better integrate genetic aspects into forest management, several countries emphasized the need to improve existing approaches for collecting

BOX 12 *CONT.*

targets large trees, honey-related mortality was disproportionately higher among large trees (up to 100 percent in the case of four tree species), which are also the most important sources of seeds and thus crucial for tree regeneration (Ribeiro *et al.,* 2019).

The work by Bioversity International and its partners included promoting non-destructive practices to gather or produce honey. In the past, wild beehives were harvested by using certain plants, rather than smoke, to tranquilize the bees, and harvesters climbed hive trees to harvest the honey instead of felling them. A honey harvester experienced in the traditional techniques demonstrated these to honey-gatherers in local communities in the Niassa Reserve. A year later, most honey-gatherers had adopted the techniques because they found them easier and less time-consuming than felling hive trees (Snook *et al.,* 2015). This change has improved the sustainability of honey-gathering because wild honey can be harvested repeatedly from the same trees while also conserving tree populations.

Sources: **Gumbo, D.J., Dumas-Johansen, M., Muir, G., Boerstler, F. & Xia, Z.** 2018. Sustainable management of Miombo woodlands – Food security, nutrition and wood energy. Rome, FAO. **Ribeiro, N.S., Snook, L.K., Nunes de Carvalho Vaz, I.V. & Alves, T.** 2019. Gathering honey from wild and traditional hives in the Miombo woodlands of the Niassa National Reserve, Mozambique: what are the impacts on tree populations? Global Ecology and Conservation, 17: e00552. **Snook, L., Alves, T., Sousa, C., Loo, J., Gratzer, G., Duguma, L., Schrotter, C., Ribeiro, N., Mahanzule, R., Mazuze, F., Cuco, E. & Elias., M.** 2015. Relearning traditional knowledge to achieve sustainability: honey gathering in the miombo woodlands of northern Mozambique. XIV World Forestry Congress, Durban, South Africa, 7–11 September 2015. http://foris.fao.org/wfc2015/api/file/552e8b8e9e00c2f116f8eac2/contents/028c3429-30dd-4b71-856b-22ea44d4849c.pdf

information on FGR as part of regular forest inventories. The data from such inventories can be used to create species distribution maps and estimate population sizes, and additional data and tissue samples can also be collected during inventories to help identify valuable genetic resources of different species and to evaluate the adaptative capacity and resilience of forests. The latter would require the further development of rapid assessment methods based on genetic markers. Countries also consider it important to develop methodologies for incorporating FGR data into forest management planning and to provide training courses on integrating genetic aspects into forest management.

Many countries indicated that mechanisms for ensuring the availability of well-documented and high-quality forest reproductive material should be strengthened to support reforestation and forest restoration efforts. Further improvement of propagation methods is also needed, especially for threatened species. Several countries called for the better documentation of deployed germplasm – that is, better record-keeping on the materials planted at a given location. This would enable managers to monitor the long-term performance of deployed material and, should problems arise later in a rotation, to better assess whether the problems are related to the geographical origin of the material or other factors.

Many countries emphasized the need to evaluate existing provenance trials and establish new ones to guide the translocation of provenances and species as the climate changes. Several noted that assisted migration should be better explained to the public and forest managers as a means for increasing awareness of the importance of FGR in adapting to climate change.

Several countries have embarked on salvage logging of forests seriously affected by insect pests and pathogens to limit further damage, but this activity could harm genetic resources if surviving trees (that presumably exhibited complete or partial resistance to the pests or diseases that otherwise caused tree damage and mortality) are felled together with the dead or damaged trees. In addition, there is a risk that economic damage stemming from climate change and invasive species reduces investments in forest management, reforestation and FGR research. Conservation units, seed stands and seed orchards could also be destroyed by abiotic and biotic disturbances, making it necessary to invest in duplication or extra seed production capacity as part of risk management strategies.

Many opportunities exist for improving FGR management. The better integration of genetic aspects into forest management and enhancing the production of well-documented and high-quality forest reproductive material will also contribute to better FGR management. Tree-breeding programmes have boosted resistance to both abiotic and biotic stressors while increasing yields. Wherever possible, therefore, the use of improved germplasm is recommended.

The identification of resistant genotypes and populations after pest or disease outbreaks should be prioritized because such trees and populations will be valuable for tree breeding and establishing new seed sources in the future. This is another reason why it is important to collect FGR data as part of regular forest inventories because the surviving trees and populations might otherwise remain hidden. There are indications in some countries that climate change and resistance breeding have increased the interest of policymakers and the public in FGR, and this may help in mobilizing more resources for FGR management.

Technologies have advanced over the last decade, offering increased opportunities to improve FGR management.[21] Range-wide studies mapping genetic diversity and threats were conducted in the last decade for an increasing number of tree species.

Legislative efforts to tackle illegal logging can be circumvented with false declarations of species and the geographical origins of wood in international timber trade, but anatomical, chemical and genetic techniques have potential for verifying claims presented in compliance documentation. A recent review (Low *et al.,* 2023) of the status of these techniques for 322 global priority timber taxa showed that reference data are available for species identification for all these taxa using wood anatomy, for 86 percent of the taxa using genetic markers and for far fewer using chemical approaches; the same review found that data for identifying geographic origin exist for only 24 percent of the taxa, with most studies applying genetic techniques.

Genetic studies for verification purposes have often targeted tropical tree species (FAO, 2014a), but such studies are increasingly being carried out for temperate and boreal tree species, such as larch (*Larix* spp.) in Asia and Europe (Blanc-Jolivet *et al.,* 2018) and bigleaf maple (*Acer macrophyllum*) in North America (Cronn *et al.,* 2021). In addition to reference data for identifying the geographic origin of wood products, these studies also make available information on range-wide genetic variation and its spatial differentiation for FGR management.

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[21] See Chapter 6 for a discussion on advances in understanding of the spatial patterns of genetic diversity and threats to enable the prioritization of conservation efforts.

10.5 Conclusions

Most countries recognize the importance of FGR as part of sustainable forest management, but this is not always reflected in practical forest management. Forest managers tend to overlook genetic aspects and often assume that FGR are safeguarded in well-managed forests without requiring specific attention. Genetic aspects are considered in forest management more frequently in planted forests than natural forests, which are commonly assumed to harbour ample genetic diversity, although their management history may be relatively undocumented. Some countries reported that awareness of genetic aspects among forest managers and policymakers has increased in recent years because of climate change, increased outbreaks of pests and diseases, and large-scale damage caused by fires and invasive species. A recent study in Europe also suggested that awareness of the importance of FGR is growing among forest owners and managers but that further efforts are needed to provide them with evidence of the benefits of considering genetic aspects (Vinceti *et al*., 2020).

To enhance the way genetic aspects are considered in practical forest management, there is a need to improve methods for collecting, archiving and making available information on FGR as part of regular forest inventories and for incorporating FGR data into forest management planning. This would allow the inclusion of specific measures for safeguarding and using FGR when developing or updating forest management plans, which guide the implementation of silvicultural interventions in the field. In the case of planted forests, there is a need to reinforce countries' capacity to produce well-documented, high-quality forest reproductive material and for forest managers to better document the deployment of this material to enable monitoring of its long-term performance. The reasons and options for assisted migration should be better explained to both the public and forest managers to boost the productivity and resilience of forests under climate change.

FGR management is challenged by many drivers of change. FGR continue to be threatened by deforestation and forest degradation, especially in the tropics, as well as by climate change, invasive species, browsing by livestock and wildlife, and the unsustainable harvesting of wood and non-wood products. Tree populations are in decline in many parts of the world.

Most country reports identified climate change as the most significant factor in the spread of insect pests and diseases and in increasing the severity and frequency of disasters such as droughts, fires and storms. Climate change is also enabling the establishment of invasive species in new areas as they spread through global trade networks. Although deforestation and forest fragmentation have slowed and some harvesting practices have become more sustainable in various parts of the world, many tree species and their populations are genetically impoverished due to the long-lasting impacts of these driving forces. Opportunities exist for improving FGR management, and these should be pursued to make forests and woodlands more resilient to climate change and to ensure the long-term sustainability of forest management.

Part 5

STATE OF CAPACITIES AND POLICIES

Chapter 11

Institutional framework for the conservation, use and development of forest genetic resources

11.1 Introduction

In the context of this report, "institutional framework" refers to relevant programmes, policies and legislation dealing with forests and FGR, as well as to structures and mechanisms supporting collaboration among stakeholders, education, research and awareness-raising (FAO, 2014a). The broad range of national institutional arrangements in countries is indicative of the cross-sectoral nature of FGR and, more generally, reflects the institutional complexity associated with environmental governance, as reported in many studies (e.g. Rodríguez Fernández-Blanco, Burns and Giessen, 2019; Zelli, Nielsen and Dubber, 2019; Engels and Rudebjer, 2017; Rayner, Buck and Katila, eds, 2010). The Global Plan of Action called on countries to strengthen aspects related to the institutional framework for FGR conservation, use and development at the national or subnational levels (FAO, 2014b). This chapter presents the status of institutional frameworks for FGR, drawn from information in country reports on national coordination mechanisms, national strategies for FGR, the mainstreaming of FGR into relevant national policies, and capacity building on FGR.

11.2 National coordination mechanisms on forest genetic resources

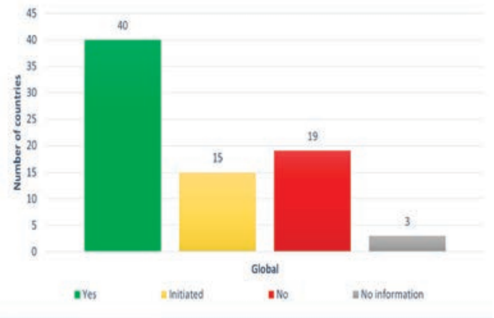
National coordination mechanisms encompass a range of approaches to the coordination of work on FGR at the national and/or subnational levels and serve as points of convergence by which stakeholders can coordinate their activities, both in the forest sector and with other sectors. Examples of stakeholders involved in the conservation, use and development of FGR are farmers, forest owners, the private sector, non-governmental organizations, governmental organizations (including state-owned enterprises), research organizations (including universities) and relevant ministries. A national coordination mechanism may take the shape of a national committee, working group or programme on FGR, depending on country-specific priorities, needs, capacities and legislation (FAO, 2025).

The Global Plan of Action stressed the need to coordinate FGR work at the national level because "knowledge on FGR is usually scattered and held by various institutions" (FAO, 2014b). It also urged the promotion of national coordination, including collaboration among institutions and programmes, and the creation of national consultation frameworks based on the willing and inclusive participation of all stakeholders (FAO, 2014b).

Of the 77 countries that made submissions for the present report, 40 (52 percent) indicated they have national coordination mechanisms for FGR in place, and another 15 countries reported having initiated the establishment of such mechanisms (Figure 20). In 2012, 33 countries had established national coordination mechanisms on FGR (FAO, 2014a); thus, seven countries (Ireland, the Islamic Republic of Iran, Luxembourg, Malta, Mexico, the Russian Federation and South Africa) established such mechanisms after 2012.

FIGURE 20

Number of countries with national coordination mechanisms on forest genetic resources



Note: Based on country reports.

Most of the reported national coordination mechanisms engage multiple stakeholder groups, as recommended in the Global Plan of Action. The main stakeholders indicated are governmental organizations (reported by 40 countries) and research organizations (38 countries) (Figure 21).

The first reported national coordination mechanisms date back more than 50 years. Countries reported a range of ministries with mandates for forests and budget allocations for FGR conservation, use and development, such as environment, agriculture, fisheries and forests, rural development, industry and trade, and natural resources and tourism. Governmental organizations with responsibilities related to FGR include state-owned forest enterprises, national seedbanks, national botanic gardens, and municipal and state forest agencies. Universities and forest research centres are examples of research organizations that conduct relevant research and development activities, such as tree-seed testing, tree breeding and the genetic conservation of priority tree species. Forest owners are also sometimes engaged in national coordination efforts, and other FGR stakeholders include farmers, non-governmental organizations (e.g. conservation organizations and farmer and forester associations) and the private sector (e.g. forest nurseries and forest industry).

In 2015, public ownership (by state, county or municipality) was the predominant category of forest ownership worldwide, accounting for 73 percent of the global forest area (FAO, 2020a). Private ownership (by individuals, enterprises, local communities and Indigenous Peoples) accounted for 22 percent, although it was the dominant form of forest ownership in some regions, such as Central America and Europe (FAO, 2020a).

The different approaches to national coordination of FGR work can be summarized as "stand-alone" (e.g. a national working group on FGR), "integrated" (e.g. integrated into a national working group on a broader topic such as forests or biodiversity but including FGR), and "fragmented" (e.g. ad hoc coordination on emerging topics involving specific stakeholders engaged in targeted FGR areas of work). The approach preferred by a country depends on the national institutional context related to FGR and forests, as well as stakeholders, processes and priorities. For example, Eswatini reported that its National Environment Office oversees the coordination of FGR work, including the equitable sharing of benefits, implemented under the second (2016) National Biodiversity Strategy and Action Plan (Government of Swaziland, 2016).[22] Eswatini's report described the coordination of FGR work as part of the biodiversity agenda as a "step towards establishing a mechanism that will be strictly for FGR". Lithuania's report stated that the country established a stand-alone national FGR advisory group in 2005 to provide "overall guidance and direction for FGR at national level". Lithuania's mechanism is chaired by the State Forest Service and the main stakeholder groups involved are governmental and research organizations. In Mexico, the work is coordinated by the stand-alone FGR Network, involving public, private and research institutions, in collaboration with other national efforts on forests, biodiversity, protected areas and plant genetic resources for food and agriculture.

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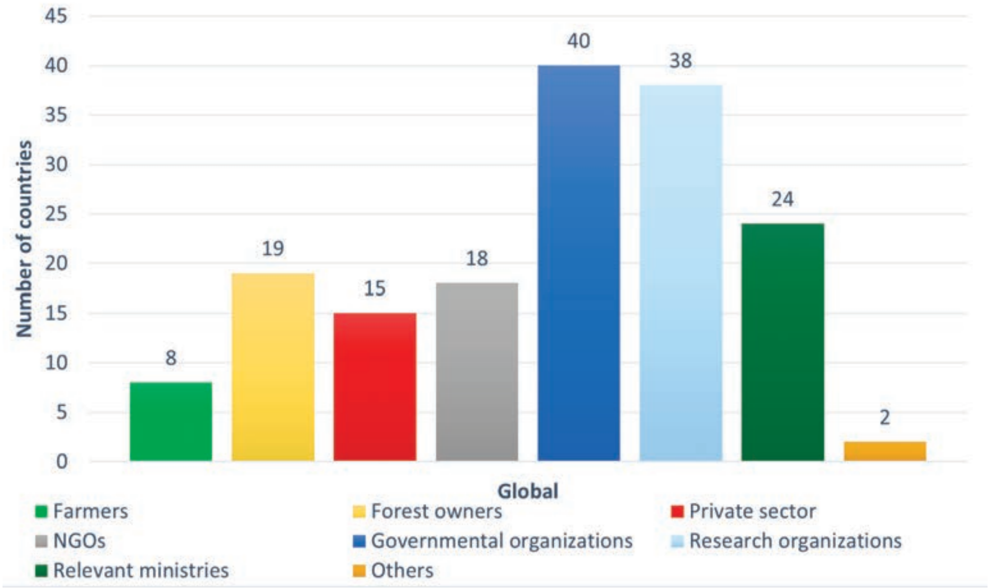
[22] Eswatini was formerly known officially as Swaziland.

FIGURE 21

Stakeholders involved in national forest genetic resource coordination mechanisms



Note: Based on country reports.

Countries that have not established national coordination mechanisms on FGR reported more-fragmented coordination efforts that targeted specific sectors or areas of work on a periodic or ad hoc basis, for example in the context of protected-area management and forest reproductive material. These countries include Chile, where FGR are managed through various parallel public- and private-sector initiatives, and Estonia, where FGR stakeholders (working on specific aspects of FGR) are consulted as needed on relevant legislative and strategic processes.

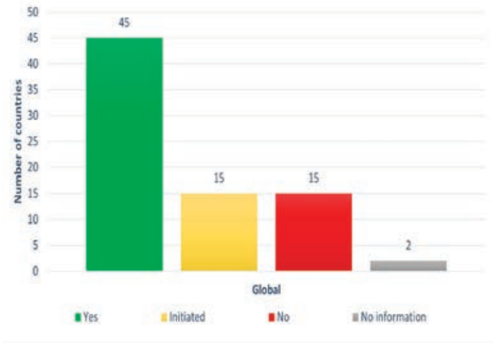
SoW-FGR1 found that coordination is often lacking and called for increased synergy and coordination among national institutions (FAO, 2014a). The present report shows that progress has been made in strengthening national coordination on FGR and that roughly half the reporting countries have national coordination mechanisms in place. The report also shows that national coordination mechanisms are engaging multiple stakeholders, although participation is often dominated by governmental and research organizations.

11.3 National strategies for forest genetic resources and integration of forest genetic resources into relevant national policies

SoW-FGR1 stressed the need for sound national policies and regulations on FGR and the integration of FGR into broader national policy frameworks to facilitate appropriate action (FAO, 2014a). Countries may follow different approaches in the preparation of national strategies on FGR, with various options for integrating FGR into relevant national policies (FAO, 2025). A national strategy on FGR should translate the country’s needs, priorities and vision related to FGR conservation,

FIGURE 22

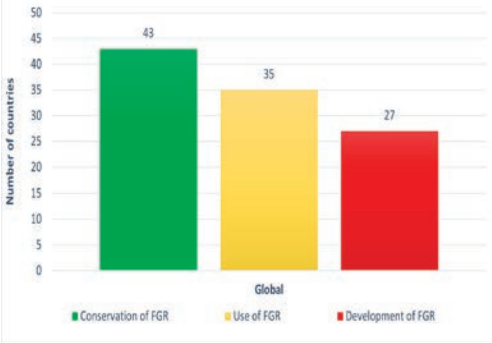
Number of countries with national (or subnational) strategies for forest genetic resource conservation and use



Note: Based on country reports.

FIGURE 23

Areas of work reported as covered by national (or subnational) strategies for forest genetic resource conservation and use



Note: Based on country reports.

use and development into a concrete, actionable framework. A key national policy is the forest policy, which describes a country's long-term goals for the development of the forest sector (FAO, 2010c), often complemented by a strategy and action plan that translate long-term policy goals into a specific, measurable and time-bound framework for action. Legislation might also be developed to facilitate the implementation of the forest policy (FAO, 2010c). Following sections present the state of national strategies for FGR and the integration of FGR into national policies related to forests, biodiversity and climate change.

SoW-FGR1 found that national policies and programmes often address FGR inadequately (FAO, 2014a). Therefore, the Global Plan of Action stressed the need for policy tools that provide a framework for action on FGR, including the development of national strategies on FGR (FAO, 2014b). National FGR strategies should be based on the national status of FGR and include descriptions of the priorities, targets, actions and responsible stakeholders and aspects related to resource mobilization and monitoring. A national FGR strategy typically aligns with existing national and subnational forest policies and national forest programmes, as well as with international instruments such as the CBD (FAO, 2025).

For this report, 45 (58 percent) of the 77 reporting countries indicated that a national (or subnational) strategy for FGR conservation and use was in place, up from 35 in 2012. Thus, ten countries[23] had prepared their national strategies since 2012 in response to the adoption of the Global Plan of Action. A further 15 countries reported that they had initiated the establishment of such strategies (Figure 22). Of the 45 countries that reported having a national strategy for FGR conservation, 24 indicated that it was aligned with their regional/subregional conservation strategies on FGR.

Most national strategies cover multiple areas of work, but FGR conservation receives most attention (as reported by 42 countries), followed by FGR use (35) and FGR development (27) (Figure 23).

The oldest national strategy on FGR, in Italy, dates to 1948. A recent example is Ireland's Sustainable Development and Conservation of Forest Genetic Resources 2020–2030 Strategy,

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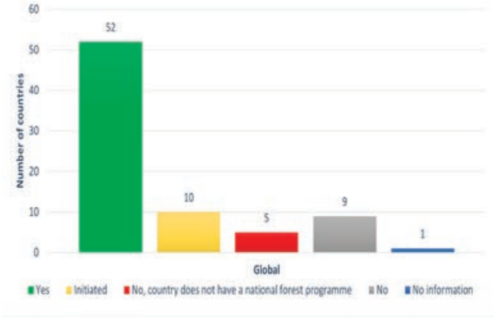
[23] China, Ecuador, India, Ireland, Japan, Kenya, Lao People's Democratic Republic, Serbia, South Africa and Sweden.

FIGURE 24

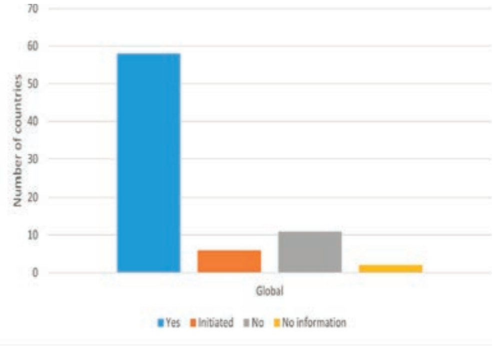
Number of countries with forest genetic resource conservation and use integrated into national forest programmes and/or national forest policies



Note: Based on country reports.

FIGURE 25

Number of countries with forest genetic resource conservation and use integrated into national biodiversity action plans and related policies



Note: Based on country reports.

which includes actions on the development and deployment of forest reproductive material, with elements on climate change, FGR development, and the genetic conservation of native tree species.

In several countries, national strategies address only certain aspects of FGR, such as the *in situ* and *ex situ* conservation of native tree species. Some countries, such as Serbia, reported that although they have national strategies on FGR in place, implementation has not yet fully started due to a lack of resources. Countries that have not yet prepared national FGR strategies reported taking strategic action in a more integrated manner, such as by addressing FGR as part of broader national strategies and plans for forests or biodiversity.

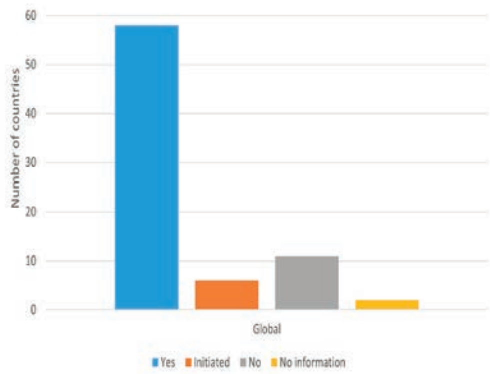
SoW-FGR1 found that national policies and programmes often insufficiently considered FGR (FAO, 2014a), and the Global Plan of Action called for the review and updating of relevant national policies, programmes, legal frameworks and regulations to integrate FGR (FAO, 2014b). FAO has prepared voluntary guidelines promoting the integration of FGR into national forest policies and national forest programmes (FAO, 2025), as well as technical guidance to support the integration of FGR into national strategies on biodiversity (FAO, 2021, 2020b) and climate-change adaptation and mitigation (FAO, 2015, 2017, 2022a, 2022b).

For the present report, 68 percent (52) of reporting countries indicated that FGR conservation and use has been integrated into national forest programmes and policies, and another nine countries said they had initiated such a process (Figure 24). A total of 58 countries reported having integrated FGR conservation and use into national biodiversity action plans (NBSAPs) and/or related policies, and six countries indicated that they had initiated a process for such integration (Figure 25). Thirty-eight countries reported having integrated FGR conservation and use into national adaptation strategies for climate change, and another 17 countries reported having initiated such a process (Figure 26).

The level of integration varies considerably among countries. An example of FGR integration with a high level of specificity is the formulation of priorities and actions to operationalize goals related to FGR conservation, use and development. A low level of specificity of FGR integration is typically expressed as a general

FIGURE 26

Number of countries with forest genetic resource conservation and use integrated into national adaptation strategies for climate change



Note: Based on country reports.

acknowledgement of the importance of FGR in relation to broader goals on forests, biodiversity and climate change but without specific actions. In Kenya, the conservation and use of FGR is embedded in the National Forest Programme 2016–2030, which informs the strategic plans of key institutes and management plans at different scales (i.e. ecosystem, landscape and plantations). Estonia reported that FGR activities have been developed under both the National Forest Development Plan and the National Climate Change Adaptation Plan. Bulgaria has formulated concrete targets on FGR under its Forestry Strategy and Action Plan. Germany reported that FGR and other agrobiodiversity sectors were integrated into the broader national strategy on biodiversity. Malta noted that FGR is integrated into its NBSAP and the substrategy, Trees & Woodlands National Strategy and Action Plan. Australia indicated that its Nature Conservation Strategy 2019–2030 integrates FGR under goal 2 on “care for nature in all its diversity”.

In general, the country reports indicate that FGR is often interpreted narrowly in forest policies as part of biodiversity conservation. Many countries reported that FGR conservation is integrated into protected-area designation and management but that the role of production forests is not considered. Harrison *et al*. (2022) highlighted this gap and proposed including FGR into the management of production forests in multiple ways as part of biodiversity mainstreaming in forestry.

An assessment of 114 NBSAPs found that, although genetic diversity is deemed important, it is often overlooked and narrowly interpreted in NBSAP implementation, monitoring and reporting at the national level (Hoban *et al.,* 2021a). A study by Hoban *et al.* (2023) of genetic diversity in the CBD’s Kunming–Montreal Biodiversity Framework stressed the importance of clear, quantifiable global goals and targets on genetic diversity and the consistent, effective and measurable implementation of genetic conservation at the national level through improved NBSAPs and related strategies.

11.4 Capacity building and education on forest genetic resource conservation, use and development

SoW-FGR1 stressed that the availability of trained and skilled professionals is a determining factor for FGR conservation, use and development (FAO, 2014a). The Global Plan of Action listed FGR education and capacity building as a priority, including by raising awareness of the importance of FGR and by increasing funding and other resources, such as field and laboratory equipment (FAO, 2014b).

As part of the Global Forest Education Project, an initiative of FAO and partners, regional assessments were prepared on the state of forest education, including the extent to which FGR was covered in curricula at the following levels: technical and vocational education and training (TVET), Bachelor, Associate, Master, and Doctoral.[24] Respondent groups comprised forest professionals,[25] teachers and students. This section presents the findings of the regional assessments (by education level) on the coverage of FGR in forest education in Africa (Kung'u, Muchiri and Kuria, 2021), Asia-Pacific (Shanahan *et al.,* 2021), Europe (Rekola, Nevgi and Sandström, 2021), Latin America and the Caribbean (Rodriguez-Piñeros, 2021), the Near East and North Africa (FAO and AOAD, 2021) and North America (Sharik and Saracina, 2021).

TVET is a type of formal education generally delivered at the secondary and tertiary levels focused on profession-based learning and specialized skill transfer (UNESCO, undated). In all six regions, most survey respondents considered that FGR was covered inadequately in their TVET curricula. Most professionals and teachers in all regions rated FGR coverage as inadequate, but most students in all regions except Asia-Pacific rated FGR coverage as sufficient.

Regarding FGR coverage in curricula at the Bachelor and Associate levels, respondents in all three respondent groups (i.e. professionals, teachers and students) generally considered it to be sufficient. Regional exceptions were Latin America and the Caribbean and the Near East and North Africa, where most respondents indicated that FGR was covered inadequately in their Bachelor and Associate curricula. In regions where most respondents found FGR coverage sufficient, such as North America, FGR was nonetheless considered a topic that needed more attention (Sharik and Saracina, 2021).

Findings were more varied across and within regions at the Master and Doctoral levels. In Africa and the Near East, most respondents viewed coverage of FGR as inadequate; in Asia-Pacific, Europe and North America, FGR coverage was generally considered sufficient. In Latin America and the Caribbean, a relatively high percentage of professionals (more than 70 percent) rated FGR coverage as inadequate, compared with teachers (50 percent) and students (45 percent).

Where FGR coverage was rated sufficient at the TVET, Bachelor and Master levels, it was only by slim margins. Of the 41 topics assessed, FGR rank highly – and in some cases highest – in all six regions in terms of the inadequacy of coverage. Therefore, all regional reports recommended increasing FGR coverage in forest education at all levels, such as by the delivery of training on seedling species identification, evaluation and assessment (Sharik and Saracina, 2021) and the creation of opportunities for professionals and students to acquire technology-based skills and familiarize themselves with new technologies (Shanahan *et al.,* 2021).

The country submissions for this report echoed the findings of the Global Forest Education Project and suggest that FGR education is seldom a well-covered discipline at the TVET, secondary and tertiary education levels. In most countries, FGR education is delivered in an integrated way – that is, FGR-related topics are covered by a course or module as part of broader, interdisciplinary curricula on natural resource management, silviculture, forest management, forest engineering, biology or plant breeding. Such courses or modules may include field or laboratory components. Canada's University of Laval teaches the importance of FGR to future professional foresters as part of a mandatory course on breeding, silviculture and reforestation. Other countries, such as Serbia and Switzerland, noted that their universities have stand-alone courses on FGR. Lebanon stressed the need to establish an explicit course on FGR to complement ongoing FGR research activities, such as those carried out by l'Université Saint-Joseph de Beyrouth.

Most countries mentioned that a gap exists between education curricula and the field-level needs of FGR users and the forest sector.

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[24] Survey question: To what extent are the following topics covered in your [TVET/Bachelor's/Master's/Doctoral] education programme? (options: inadequately, sufficiently or excessively covered).

[25] Professionals working with government agencies, non-governmental organizations, forest owners' associations, business organizations and labour unions.

Greece reported that, although forest genetics and tree breeding are mandatory for obtaining a Bachelor's degree, there is a need for stand-alone FGR courses and programmes to sufficiently familiarize forest professionals with FGR. In its report, China highlighted the need for technical training for field forestry staff and improved access to online and offline learning materials to build the capacities of local forest workers and farmers and the public. Sweden was one of only a few countries that reported the existence of a specialized stand-alone education programme on FGR. Established in 2013, the Industrial Graduate Student Research School of Forest Genetics, Biotechnology and Breeding is a five-year postgraduate academia–industry programme on the molecular genetics of prioritized traits, genomics, somatic embryogenesis, statistics, quantitative genetics, and breeding theory.

Overall, survey respondents reported limited enrolments in forest-related programmes; reasons put forward for the declining popularity of forest education included reduced attractiveness and financial support and a perceived mismatch between forestry curricula and the labour market. These reasons correspond with the findings of the Global Forest Education Project and its regional assessments (Rekola and Sharik, 2022). A notable exception is Brazil, which reported an increase in the number of courses and degrees on forest-related topics between 1995 and 2021. Brazil's courses and degrees have a regional (Latin America) and broader international reach in terms of student enrolments.

Although the coverage of FGR in curricula varies by region and education level, all regional reports recommended increasing FGR coverage in forest education across all levels. The country reports support the findings of the Global Forest Education Project survey on the need to increase FGR coverage in forest education at all levels, with calls to improve FGR education, especially at the TVET level; train professionals and students to respond to the current and future needs of the forest sector; and support FGR stakeholders with field-level activities.

11.5 Conclusions

SoW-FGR1 (FAO, 2014a) and the Global Plan of Action (FAO, 2014b) recommended strengthening the institutional framework for the conservation, use and development of FGR. The findings of the present report show that some progress has been made to strengthen the institutional frameworks for FGR in reporting countries (for example with respect to national coordination mechanisms, national strategies on FGR and relevant national policies), as well as education.

Progress has been made in integrating FGR into relevant national policies, programmes and strategies. Fifty-eight percent of reporting countries have developed national strategies on FGR, most of which cover multiple areas of work, although FGR conservation is integrated into relevant national strategies more frequently than FGR use and development. FGR considerations are better integrated into national policies on forests and biodiversity than national climate-change adaptation strategies. The way FGR considerations have been integrated into relevant national policies varies in their specificity, ranging from concrete sets of action on FGR to more general acknowledgement of the importance of these resources.

The progress reported by countries also indicates a continued need for countries to improve their institutional frameworks for the conservation, use and development of FGR, taking into consideration their capacities and priorities. In identifying possible actions for strengthening institutional frameworks to promote FGR conservation, use and development, countries are encouraged to consider all areas of FGR work, engage all stakeholders, and identify specific actions on FGR. The broad range of national (or subnational) institutional frameworks reported highlights the institutional complexity and cross-sectoral nature of FGR governance and the need to take into consideration all stakeholders and their needs and priorities in developing national institutional frameworks for the conservation, use and development of FGR.

Chapter 12

International and regional cooperation on forest genetic resources

12.1 Introduction

The natural ranges of many trees and other woody plants extend across countries and even regions, making international and regional cooperation on FGR crucial (FAO, 2014a). People have been moving FGR within and outside the natural ranges of species for forestry purposes and research and development for the last 200 years (Koskela *et al*., 2014). SoW-FGR1 recognized that political borders are irrelevant for many of the drivers affecting FGR, such as climate change and pests and diseases (FAO, 2014a). Therefore, the interdependence of countries in managing and conserving FGR is expected to increase.

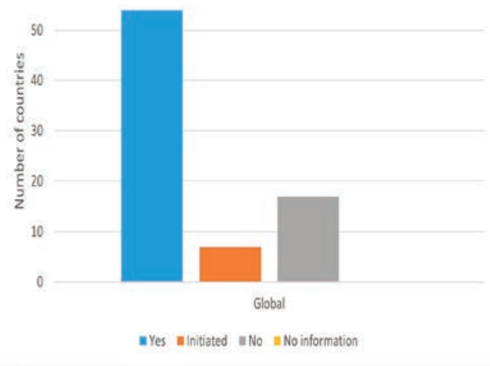
International cooperation on FGR dates to the nineteenth century under the auspices of the International Union of Forest Research Organizations (IUFRO), and it gathered pace in the 1950s as interest grew in tree improvement and breeding for plantation purposes. Range-wide seed collection missions were conducted in the 1960s and 1970s to establish international provenance trials for various tree species, especially in the tropics, and international collaboration on FGR research also intensified. These efforts continued in the 1980s and diversified into a wider range of multipurpose species. For some species, such as neem (*Azadirachta indica*), leucaena (*Leucaena leucocephala*) and teak (*Tectona grandis*), global interest led eventually to the establishment of species-specific networks. In the 1990s, especially in the wake of the woodfuel crisis and growing realization of the importance of multipurpose woody species for rural livelihoods, special efforts were made to establish international species and provenance trials in arid and semi-arid regions. FAO, advised by the Panel of Experts on Forest Gene Resources, was instrumental and closely involved in many of these efforts in the 1990s and, in collaboration with national and international partners, also helped convene regional and subregional workshops on FGR in various parts of the world (Palmberg-Lerche, 2001, 2007). Several regional programmes and projects on FGR were established in the 1990s (e.g. EUFORGEN, the Sub-Saharan African Forest Genetic Resources Programme – SAFORGEN, and the South Pacific Regional Initiative on FGR), many of which are still operational.

Based on the findings of SoW-FGR1, the Global Plan of Action called for the reinforcement of international and regional cooperation, including by mobilizing the necessary resources, to enhance the management of FGR (FAO, 2014b). Collaboration is an important aspect – one-third of the Global Plan of Action's strategic priorities address international and regional cooperation.

SoW-FGR1 provided mainly qualitative information on collaboration on FGR (FAO, 2014a). An effort has been made for the present report to gather quantitative data: based on these data, this chapter discusses the state of countries' participation in international FGR research and development and in regional FGR networks. It also provides summaries of the main international and regional cooperation mechanisms mentioned by countries in their reports and summarizes the experiences of countries in this area.

FIGURE 27

Number of countries participating in international research and development cooperation on forest genetic resources



Note: Based on country reports.

12.2 Participation in international and regional cooperation on forest genetic resources

The extent of countries' involvement in international and regional cooperation on FGR is a key indicator of global commitment with respect to these crucial resources. This section outlines the participation of countries in such cooperation, emphasizing their engagement in research and development, networks and programmes related to FGR.

Of the 77 reporting countries, 54 (70 percent) indicated that they participate in international research and development collaboration on FGR (Figure 27), such as in global, regional and subregional research projects, tree-breeding programmes, and various other research and development efforts aimed at enhancing the use, management and conservation of FGR. An additional seven countries reported having sought opportunities to engage in collaborative initiatives. Cooperation is taking place in all regions (Figure 28), with countries in Asia, Europe, Latin America and the Caribbean, and North America demonstrating high levels of involvement in international collaboration, as indicated by the number of participating national institutes (Figure 29). Not all countries reported active participation or provided substantial information on such involvement. A common barrier identified by those countries was the lack of adequate funding and resources, which significantly impeded their ability to engage in international cooperation on FGR.

Active participation in international FGR cooperation typically necessitates not only funding but also a certain level of technical expertise and infrastructure. These prerequisites may not be fully developed in some countries. National policies and the priority assigned to FGR conservation and use play pivotal roles in determining the level and nature of international cooperation.

Globally, 55 of the reporting countries (71 percent of respondents) indicated that they participate in regional or subregional FGR networks, and an additional seven are considering joining such networks (Figure 30). The majority of countries in each of Africa, Asia, Europe and North America reported participating in these networks (Figure 31). Despite this high level of engagement, more information is needed on the participation of countries in the regional networks to gain a better picture of the state of regional network participation.

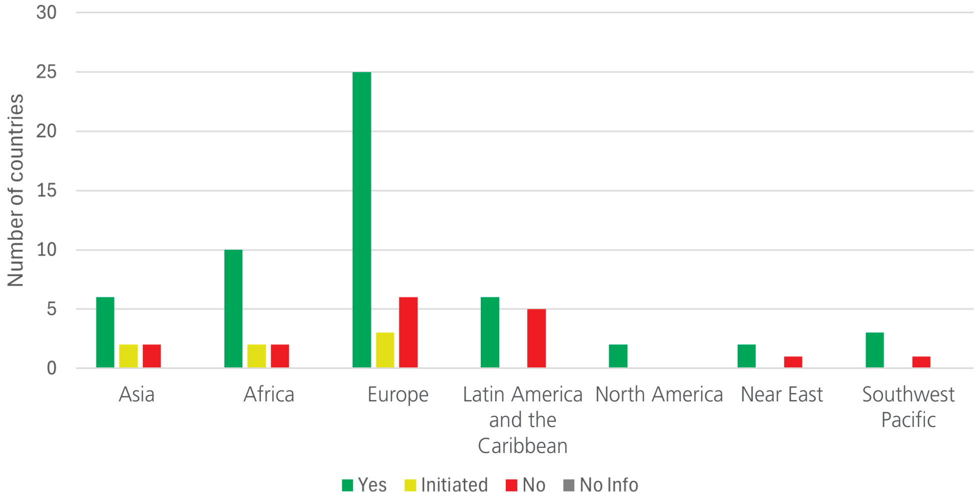
Differences in participation between countries can be attributed to a few factors. For example, financial and organizational constraints can hinder countries from actively engaging in regional FGR initiatives and participating in international meetings and networks.

12.3 Actors in international and regional cooperation on forest genetic resources

In their reports, countries identified diverse platforms in which they are participating and organizations with which they are collaborating. These can broadly be grouped into global

FIGURE 28

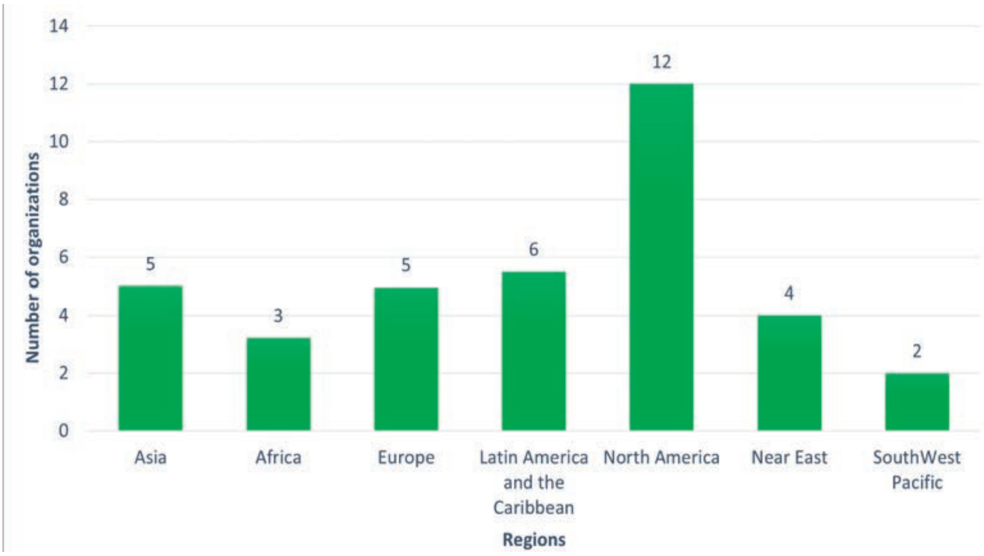
Number of countries participating in international research and development cooperation on forest genetic resources, by region



Note: Based on country reports.

FIGURE 29

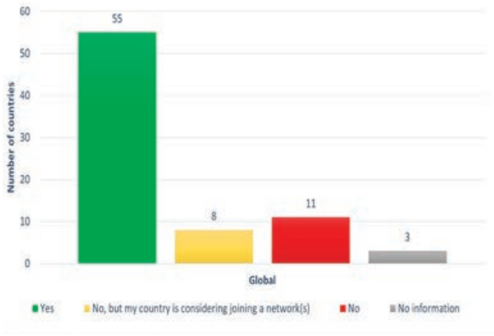
Average number of national organizations participating in international research and development collaboration on forest genetic resources, by region



Note: Based on country reports.

FIGURE 30

Number of countries participating in regional or subregional networks on forest genetic resources



Note: Based on country reports.

networks, regional or ecoregional networks, and international and other organizations. Networks and organizations are pivotal for enabling and advancing global and regional cooperation on FGR. The main platforms identified by countries, and their activities, are presented in the following sections.

Global networks

IUFRO, established in 1892, is a global network of forest scientists promoting international cooperation in forest-related research and enhancing understanding of the ecological, economic and social aspects of forests and trees (IUFRO, 2023). It brings together more than 15 000 scientists from about 630 member organizations in almost 120 countries. IUFRO has a long history of promoting international cooperation and research on FGR through its Division 2, which focuses on the physiology and genetics of forest trees (IUFRO, 2023). In its Post-2020 Strategy, IUFRO aims to bolster its position as the global nexus for forest science cooperation, knowledge-sharing and policy support (IUFRO, 2020).

BGCI, established in 1987, is a global network of about 3 000 botanic gardens and arboreta in more than 100 countries. Since 2018, BGCI has been leading the Global Tree Assessment (BGCI, 2024b), the aim of which is to assess the conservation status of all the world's known tree species. BGCI maintains several databases for this purpose, including GlobalTreeSearch (BGCI, 2024a), which provides the most comprehensive list of tree species and their natural distribution. In 2021, BCGI published a global report that assessed the conservation actions in place for tree species and threats to them. BGCI has also developed training materials and accreditation schemes to bolster conservation efforts and ensure compliance with international regulations (BGCI, 2021).

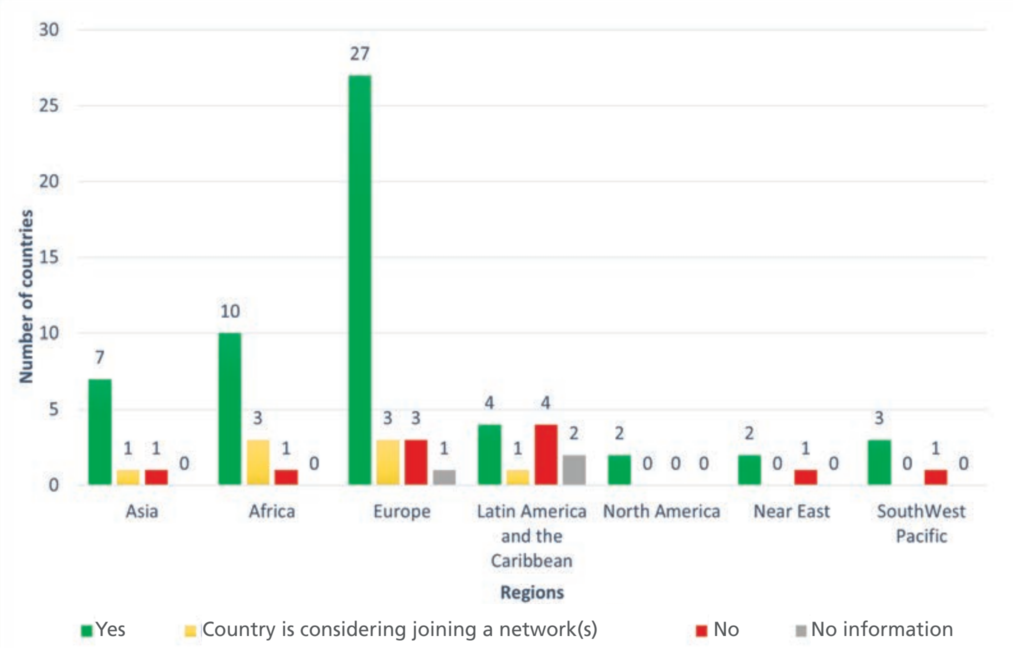
The International Teak Information Network (TEAKNET), founded in 1991, is a global network of institutions and individuals interested in teak (*Tectona* spp.); its secretariat is hosted by the Kerala Forest Research Institute in Peechi, India. TEAKNET is committed to fostering information-sharing among diverse teak stakeholders, including growers, traders and researchers. The network is not only a conduit for knowledge exchange but also deploys initiatives that propel the teak sector forward to ensure its sustainable growth (TEAKNET, 2020). TEAKNET co-hosts World Teak Conferences, which bring together more than 70 teak-growing countries. TEAKNET has also been instrumental in publishing periodicals, bulletins and reports on the teak industry. It collaborates with FAO, IUFRO and the International Tropical Timber Organization to promote the sustainable management of teak resources.

Regional and ecoregional networks

Silva Mediterranea, the Committee of Mediterranean Forestry Questions, was established in 1948 as a statutory body of FAO. Its participants are member countries of the European Forestry Commission, the Near East Forestry Commission and the African Forestry and Wildlife Commission. *Silva Mediterranea* enables the sharing of experiences and promotes cooperative programmes on sustainable forest management. It has several working

FIGURE 31

Number of countries participating in regional or subregional networks on forest genetic resources, by region



Note: Based on country reports.

groups, including one on FGR. In collaboration with partners, *Silva Mediterranea* organizes Mediterranean Forest Week, a biennial event that serves as a regional platform for cooperation on Mediterranean forests.

The FAO North American Forestry Commission (NAFC) established the Forest Genetic Resources Working Group in 1961, which focuses on the conservation and sustainable use of North American forest trees. One of the most active NAFC working groups, it promotes information exchange, coordinates research and conservation efforts, facilitates international exchanges of FGR, and endorses genetic improvement programmes for key commercial forest species (NAFC, 2023).

Another example of North American collaboration is the Updated Silvics of North America (USNA) project, which is updating knowledge on the silviculture of the region's tree species (Burns and Honkala, 1990). The original Silvics of North America had chapters on 198 species, and the USNA project will expand this to more than 300 species in three species groups (i.e. conifer, deciduous and invasive). Each chapter will have information on current and projected species ranges, climate-change impacts, species genetics, and species use by Indigenous Peoples. About 250 scientists from Canada, Mexico and the United States of America are contributing to the project, led by the Southern Research Station of the United States Forest Service.

EUFORGEN was established in 1994 to implement a resolution on FGR made by the first Ministerial Conference on the Protection of Forests in Europe (now called Forest Europe). Since then, the Forest Europe process has frequently reaffirmed the role of EUFORGEN in facilitating pan-European collaboration on FGR. EUFORGEN released the first pan-European strategy for the genetic conservation of forest trees in 2015 and established a core network of dynamic genetic conservation units. Its latest strategy, the FGR Strategy for Europe, contributes to the implementation of regional-level strategic priorities of the Global Plan of Action (EUFORGEN, 2021), with the aim of unifying the conservation and sustainable use of FGR across the continent. The strategy also introduces new methods for accurate FGR characterization and calls for the expansion of scientific knowledge. It emphasizes the importance of genetic diversity for forest resilience, particularly in the face of climate change and other environmental challenges, and sets a clear path for future collaborative actions with the aim of enhancing the long-term health and adaptability of Europe's forests. EUFORGEN continues to maintain the European Information System on Forest Genetic Resources, which, as of 2024, contains information on more than 3 400 genetic conservation units for more than 100 tree species in 37 countries (EUFORGEN, 2023). In 2020, EUFORGEN updated indicators for *in situ* and *ex situ* genetic conservation (Lefèvre *et al.*, 2020) as part of the pan-European criteria and indicators for sustainable forest management adopted by the Forest Europe process.

European country reports also referred to two other platforms, EVOLTREE and the Nordic Genetic Resource Centre (NordGen). EVOLTREE was funded initially by a European Commission research programme but has operated since 2011 as a self-sustaining European Research Group. The aim of the network is to address global issues such as environmental change and biodiversity erosion by linking four major disciplines – ecology, genetics, genomics and evolution. EVOLTREE is a platform for collaborative research on FGR and knowledge exchange by maintaining research infrastructure and organizing training and conferences. In fostering collaboration and providing resources, EVOLTREE contributes to the uptake of research findings in the sustainable management and conservation of FGR in Europe (EVOLTREE, 2024).

NordGen is dedicated to the conservation and sustainable use of genetic resources related to cultivated plants, farm animals and forest trees in the Nordic region. One of its specialized branches is NordGen Forest, which focuses on aspects of forest regeneration and conservation and aims to enhance the quality of Nordic forests for future generations through various initiatives. NordGen Forest operates with the support of two key networks that bring together members in the Nordic countries – the NordGen Forest Regeneration Council and the NordGen Forest Working Group on Genetic Resources.

SAFORGEN was established in 1998; until recently it has been coordinated by Bioversity International, a function now performed by the Alliance of Bioversity International and the Center for International Tropical Agriculture ("the Alliance"). The main goals of SAFORGEN are to study forest genetic diversity, develop strategies and methods for conserving and sustainably using forest biodiversity, and disseminate knowledge and information on FGR. It focuses on essential tree groups such as food trees, medicinal trees, trees for wood and fibre, and fodder trees (SAFORGEN, 2011). Bioversity International and FAO convened a regional workshop in 2016 in Douala, Cameroon, to support implementation of the Global Plan of Action in sub-Saharan Africa. The workshop brought together the SAFORGEN national coordinators and other experts to discuss the strategic priorities of the Global Plan of Action and develop a regional strategy to support its implementation. The workshop also identified the most relevant strategic priorities for the region, as stated in reports received from international organizations.

Another regional workshop was held in Kumasi, Ghana, in 2019 to exchange information on country activities, discuss challenges related to implementation of the regional strategy and ways to strengthen tree-seed systems in sub-Saharan Africa, and agree on steps to strengthen the network. The workshop agreed that SAFORGEN would continue with three working groups on tree breeding and seed production systems; the characterization of FGR and data systems; and *in situ* and *ex situ* conservation of FGR.

APFORGEN was established collaboratively in 2003 by the Asia Pacific Association of Forestry Research Institutions, the International Plant Genetic Resources Institute and FAO and now has 15 member countries. APFORGEN developed a regional strategy jointly with its member countries to support implementation of the Global Plan of Action. When the strategy was updated for 2023–2030 (APFORGEN, 2023), its targets were aligned to support countries in implementing the Kunming–Montreal Global Biodiversity Framework. The strategy is implemented primarily by raising funds for collaborative multicountry research and capacity-development projects. Through its programmes, APFORGEN has published distribution and threat maps for 63 native regionally important tree species since 2018 (Gaisberger *et al*., 2022a); developed spatially explicit genetic conservation assessment methods; and published assessments of the extremely valuable rosewood species (Gaisberger *et al*., 2022b). It has also developed seed-zone maps, information systems and local capacities to improve the availability of high-quality germplasm of native trees for meeting national forest restoration targets (APFORGEN, 2024) and published more than 20 multicountry studies, reports and guidelines on the conservation and sustainable use of the region's FGR. Since 2016, APFORGEN has been operating a regional training centre, which runs workshops and provides distance-learning opportunities on the conservation and management of FGR for trainers, policymakers, forest managers and researchers; it has trained over 200 professionals from 17 countries (Jalonen, Yongqi and Warrier, 2024). APFORGEN's strategy has been endorsed by the Asia-Pacific Forestry Commission, which highlighted the importance of regional collaboration for strengthening capacities to document and conserve the region's vast FGR (FAO, 2018d). APFORGEN's results have been adopted in government training programmes, policy revisions (Jalonen *et al*., 2024) and global conservation assessments, including the IUCN Red List of Threatened Species (Barstow *et al*., 2022a, 2022b). APFORGEN seeks further opportunities to collaborate with national, regional and international organizations to expand its reach and impact.

The Latin America Forest Genetic Resources Network (LAFORGEN) was established in 2006 following an expert consultation workshop in Cali, Colombia, organized by Bioversity International and Spain's National Institute for Agricultural and Food Research and Technology. LAFORGEN's goals include promoting the conservation and sustainable use of FGR in Latin America, fostering collaboration between countries, facilitating information exchange among professionals, supporting research activities of mutual interest, and conducting training related to the network's objectives. Various efforts have been conducted recently to rejuvenate the network's activities, as reported by the Alliance.

International and other organizations

The Royal Botanic Gardens, Kew (RBG), which was established in 1759, operates botanic gardens in London and Sussex in the United Kingdom of Great Britain and Northern Ireland and conducts research around the world to better understand and protect plants and fungi. RBG houses the world's largest botanical and mycological collections and has developed databases for plants and fungi, such as the Plants of the World Online database (RBG, 2024). Its facilities include a research station in Madagascar and the Millennium Seed Bank in Sussex, the latter conserving seeds from more than 6 700 tree species. RBG carried out 17 projects between 2012 and 2022 that have contributed to the conservation of FGR in 20 countries worldwide. Among other things, these projects have strengthened the contributions of primary forests and protected areas to the *in situ* conservation of FGR and promoted the establishment and development of *ex situ* conservation systems. They have strengthened the role of forests managed by Indigenous Peoples and local communities in FGR conservation and assessed the conservation status of rare, threatened and highly useful tree and woody plant species. RBG has implemented projects that support reforestation, land rehabilitation and the sustainable use of plant resources and that promote the use of emerging technologies in conservation. It has also contributed to the development of national strategies, promoted regional and international cooperation, and mobilized resources for FGR conservation and sustainable use (RBG, 2022).

The OECD is an international body committed to promoting policies that improve the economic and social well-being of people worldwide. Established in 1961, the OECD provides a platform for governments to work together, share experiences and seek solutions to common challenges. It operates the Forest Seed and Plant Scheme (OECD, 2018), which is designed to standardize and certify the origin and quality of forest reproductive material for international trade. Thirty countries participate in the scheme, including several developing countries, which defines four broad categories of forest reproductive material recognized for certification: (1) source-identified material (minimum standards); (2) material from selected stands located in well-delimited regions of provenance; (3) qualified material from untested seed orchards; and (4) tested material from tested seed orchards or stands that can produce seed of improved quality. The scheme continues to collaborate with governments, international organizations and industry representatives to regularly update its standards, reflecting the evolving needs of the forest sector and the challenges posed by changing environmental conditions (OECD, 2022).

Bioversity International, established in 1974, created an alliance with the Center for International Tropical Agriculture in 2019 to continue delivering research-based solutions to harness agricultural biodiversity and sustainably transform food systems to improve people's lives. Through interdisciplinary research conducted globally, Bioversity International focuses on building an evidence base, decision-support tools and capacity to support the safeguarding and sustainable use of diverse forest resources, as well as the resilient restoration of degraded landscapes using tree diversity. Bioversity International has supported the identification of priority tree species at the local, national and regional levels based on a combination of biological and socioeconomic factors. In the last ten years, Bioversity International and its research partners have conducted several multispecies threat analyses and other studies in tropical Asia, Africa and Latin America. It also coordinates the LAFORGEN and SAFORGEN networks and contributes to APFORGEN's activities.

World Agroforestry (ICRAF), which was established in 1978, promotes agroforestry research and the conservation, improvement and delivery of tree genetic resources. With the creation of its Genetic Resources Unit in 1990 and the establishment of the ICRAF gene bank in 1997, ICRAF hosts the world's most extensive collection of agroforestry tree genetic resources. The ICRAF Genebank in Nairobi, Kenya, safeguards more than 6 000 seed accessions of 190 species. Another 17 000 accessions of more than 681 species are held in 49 field gene banks located in 18 countries in Africa, Asia and Latin America. ICRAF joined forces with the Center for International Forestry Research in 2019, and trees and FGR are one of the priority research themes of the combined institution (known as CIFOR–ICRAF). As part of the CGIAR Consortium Research Programme on Forest Trees and Agroforestry (2011–2021), ICRAF led the Flagship on Tree Genetic Resources for Productive and Resilient Landscapes, addressing significant constraints in the diversity and genetic quality of the tree seeds and seedlings supplied to planting programmes (Graudal *et al*., 2021). ICRAF has developed tools relevant to FGR, such as the Agroforestry Species Switchboard (Kindt *et al*., 2022) and the Global Tree Knowledge Platform (GTKP) (Kindt *et al*., 2021). The Switchboard provides access to more than 50 web-based information sources on trees and other plants for more than 172 000 plant species, and the GTKP contains a wide range of tree knowledge products (World Agroforestry, 2023a). The GTKP also provides access to maps modelling the effects of climate change on the distribution of tree species in Africa and Central America (World Agroforestry, 2023b). Moreover, the GTKP makes available guidelines and statistical tools that can assist users in performing their own analyses and to find resources useful for the management of FGR, and it assists capacity development (see, for example, Schmidt *et al*., 2021). CIFOR–ICRAF is supporting the strengthening of national tree-seed programmes in several countries in Africa.

Tree-breeding cooperatives, which are often commercially driven, also play a crucial role in the conservation and use of FGR. In Australia and the United States of America, such cooperatives have been central to FGR management, balancing economic and ecological goals by improving commercially important tree species and conserving their valuable genetic resources. The Central America and Mexico Coniferous Resources Cooperative (Camcore), which was established in 1980 and is hosted by North Carolina State University, is an example of an international tree-breeding cooperative; it has 27 members in 11 countries in Africa, Asia, Latin America and North America (Camcore, 2024). Camcore works internationally with four genera – *Eucalyptus*, *Gmelina*, *Pinus* and *Tectona* – in tropical and temperate regions, as well as with threatened tree species native to the southern United States of America.

12.4 Country experiences in international and regional cooperation

Many countries have participated in international cooperation on FGR for more than 60 years. The multitude of projects and initiatives reported by countries, as well as the many regional networks and international organizations, show that the commitment to enhancing the conservation, use and development of FGR continues.

The benefits of international and regional cooperation are many. For example, Brazil, El Salvador and Lebanon each indicated that cooperation has contributed to the sharing of knowledge and the development of methodologies and strategies for FGR conservation and management. Other countries also referred to the importance of international cooperation for FGR management and for developing related policies. El Salvador reported that its involvement in several networks has helped improve the quality and productivity of reforestation programmes. China noted that its active participation in various international networks stems from its FGR research work. Several countries reported funding FGR projects, demonstrating commitment to international collaboration and to building a global FGR knowledge base.

Cooperative initiatives in the Nordic countries have led to more robust genetic diversity management by enabling the development of shared strategies for managing FGR across the Nordic region. Collaboration in North America has resulted in the standardization of methodologies for conservation genetics research. This standardization is crucial for ensuring consistency in the data collected and approaches used, which in turn facilitates comparative research and more effective management strategies across the continent. In Asia and the Southwest Pacific, several networks and initiatives facilitate information and exchange, as well as joint research on FGR.

Cooperative networks provide platforms for exchanging knowledge and best practices, which enhance the capacity of participating countries to manage their FGR more effectively, is vital for innovating and improving conservation strategies, and offers opportunities for countries to learn from each other’s experiences. Collaborative efforts also foster enhanced research and development. By combining scientific capabilities and resources, countries in these networks can undertake comprehensive studies that address pressing issues such as pest and disease management, climate adaptation strategies and the restoration of degraded forest lands.

International and regional cooperation also aids the development of unified policies, which are crucial for the effective transboundary management of FGR. Unified policies help manage the cross-border flow of genetic materials and ensure that conservation efforts are harmonized and more effective at a regional scale. Initiatives undertaken at the national and regional levels are indicative of a ground-up approach to FGR conservation. By harmonizing strategies within regions, countries can develop more cohesive and context-specific responses to conservation challenges. This is particularly relevant in regions sharing common species, environmental features or challenges. Moreover, national and regional cooperation allows the customization of international directives to fit local circumstances, thus helping ensure that global objectives are met while also respecting and incorporating local needs and priorities.

Regional research collaborations, such as those in Asia, Europe and North America, serve as platforms for advancing scientific understanding and applying it to the management of FGR. These networks create a shared pool of data and resources that can significantly increase regional capacity for FGR conservation. The success of regional cooperation, however, is contingent on overcoming challenges such as ensuring equitable participation, maintaining funding, and fostering long-term commitment among member countries. The extent to which Nagoya and other CBD-related regulations hinder cross-border collaboration and exchange of FGR poses a significant challenge. These regulations, which help safeguard biodiversity and ensure fair benefit-sharing, can create legal and administrative barriers to the sharing of FGR between countries. The effectiveness of regional networks and initiatives hinges on their ability to remain adaptable and responsive in navigating these regulatory frameworks.

The Global Plan of Action stressed cooperation on capacity building, with many countries investing in initiatives to enhance knowledge, skills and community engagement in this field. Capacity building, in this context, encompasses various educational, training and community engagement initiatives that enhance the skills and knowledge necessary for effective FGR management, from educational programmes to hands-on training. Several countries reported that international and regional cooperation supports capacity building through educational programmes and in-person or online training initiatives, ranging from postgraduate courses to specialized workshops. International education programmes serve a dual purpose: they contribute to the global knowledge base and foster international networks of professionals. This is pivotal for creating a globally coherent approach to FGR conservation, whereby expertise can be shared and applied in different geographic and cultural settings. Argentina’s contribution to capacity building through postgraduate training and research collaboration exemplifies this approach, as does the involvement of Australia and Canada in international collaborative projects that enhance domestic research capabilities and contribute to the global knowledge base on FGR. Brazil’s efforts in this area show that international cooperation can be a powerful tool for building technical and commercial capacity. It can also help improve methodologies and strategies for FGR conservation and management.

Challenges remain in capacity building, including resource limitations and the integration of traditional knowledge with scientific research. Addressing such challenges requires ongoing collaboration and innovation among countries.

12.5 Conclusions

The country submissions for the present report indicate that the landscape of international cooperation in FGR is dynamic and multifaceted. Collective efforts are addressing both global conservation goals and local management needs, reflecting a holistic approach to FGR conservation. Regional networks are showing the practical benefits of proximity and shared ecological regions in developing cohesive strategies for FGR conservation. They facilitate the pooling of resources, exchange of expertise and development of regionally adapted solutions to common problems. Progress has been made in strengthening international and regional cooperation on FGR over the last decade, and countries are showing ongoing interest and commitment to this. Cooperation has proved indispensable for the implementation of the Global Plan of Action and needs to continue, which requires that, in all regions, funding, engagement and capacity building are addressed.

Funding for international cooperation that is inclusive of all countries will ultimately benefit all participating parties. Conversely, there are risks associated with inaction or fragmented efforts, including the loss of genetic diversity and resources, ecosystem degradation and the possible extinction of species. It is through joint endeavours in research, resource management and policymaking that these risks can be tackled. Strong, collaborative efforts enable the pooling of resources, the harmonization of conservation practices and the protection of forest resilience and genetic diversity while also avoiding the duplication of efforts, all of which have far-reaching global benefits.

Part 6

CHALLENGES AND OPPORTUNITIES

Chapter 13

Recommended actions for the future

13.1 Introduction

The present report was prepared at the request of the Commission on Genetic Resources for Food and Agriculture to analyse how the state of the world's FGR might have changed since adoption of the Global Plan of Action (FAO, 2014b) and to monitor the progress on implementation of the plan. The Global Plan of Action identified 27 strategic priorities, many of which are closely related and interlinked. They are grouped into the following four priority areas:

1. improving the availability of, and access to, information on FGR;
2. conservation of FGR (*in situ* and *ex situ*):
3. sustainable use, development and management of FGR; and
4. policies, institutions and capacity building.

A decade is a short period compared with the lifespans of most forest trees and other woody plants. Nevertheless, the findings of the present report show that progress has been made in all four priority areas, albeit to varying degrees. The findings also provide a more refined picture of the state of FGR conservation, use and development around the world than SoW-FGR1, even though fewer countries made submissions for the present report.

The four priority areas of the Global Plan of Action encompass a total of 78 actions, including detailed activities. The high number, and the fact that many of these actions are relevant to more than one priority area, make it challenging to assess the progress made. Recognizing this complexity, the Commission adopted targets, indicators and verifiers for monitoring implementation of the Global Plan of Action based on higher-level actions in the four priority areas rather than tracking each priority action. The Commission used the same approach when it adopted the reporting guidelines for the present assessment.

The following sections summarize the progress made in each of the four priority areas and recommend higher-level actions for the coming decade.

13.2 Availability of, and access to, information on forest genetic resources

Progress has been modest since SoW-FGR1 in improving the availability of, and access to, information on FGR. Many countries lack national FGR inventories that would systematically gather and analyse data on FGR and all areas of work on FGR. In countries with such inventories in place, there are often information gaps because not all stakeholders involved in FGR management at the national level contribute to the inventories.

The reports submitted by some countries had minimal content and lacked species-specific data on efforts to conserve, use and develop FGR. This lack of detail is compounded by the fact that more than half the Commission's members failed to make submissions for the report. Thus, in many developing and developed countries, the availability of even basic information on

FGR is limited, with the effect that policymakers and practitioners are likely unaware of the importance of FGR and the actions needed. The lack of information also hinders efforts by the international community to better integrate FGR into global policies.

Commonly, the gathered information is accessible only to the stakeholder who collected it, or the data are stored in stakeholder databases without any effort to disseminate them to policymakers, practitioners and the public. This is due largely to the lack of national FGR information systems, through which stakeholders could report information or to which they could connect their own databases. As a result, information is often scattered at the national level, which hampers countries in their efforts to improve FGR management, develop relevant policies and advance research and development on FGR.

If unaddressed, this situation will continue to hamper implementation of the Global Plan of Action and future global FGR assessments. Many countries need to act to improve the availability of, and access to, information on FGR. In many cases, this will require international cooperation, including within regions.

The overall status of forest biomes and trees and other woody plants is monitored well and frequently at the national and international levels. The genetic diversity of trees and other woody plants are not monitored systematically over time, however, and operational genetic monitoring systems are in their infancy. Although there is evidence of genetic erosion in species, the extent of genetic diversity loss is largely unquantified because of the lack of temporal genetic data in most countries. This is a major gap in information on FGR. Some countries have started to address this gap with specific genetic monitoring systems, but most are yet to take such action or have conducted one-off assessments of genetic diversity in selected species. Most countries do not systematically gather and store information on the non-molecular and molecular characterization of trees and other woody plants. It is crucial, therefore, to strengthen genetic monitoring and characterization efforts at the national level.

The conservation, use and development of FGR are important for sustainable development, including sustainable forest management, and for global efforts to conserve biodiversity, mitigate climate change and combat desertification. Policymakers, practitioners and the public, however, often overlook the importance of FGR. In their reports, several countries noted that the limited availability of information on FGR has hindered efforts to raise awareness of the importance of FGR. FGR is also neglected in global frameworks on sustainable development, biodiversity, climate change and sustainable forest management. Therefore, although efforts are underway to improve the availability of information on FGR, it is crucial to strengthen national, regional and global actions to increase awareness of the importance of FGR.

The preparatory process of this report, and especially the regional meetings organized for national focal points and other national experts, increased understanding of technical terms, concepts and approaches related to the conservation, use and development of FGR. The targets, indicators and verifiers adopted by the Commission for monitoring implementation of the Global Plan of Action also proved useful for improving data collection for the present report. Nevertheless, some indicators and verifiers are still interpreted in different ways by the national focal points, and the term "forest genetic resources" is also understood differently among countries. Thus, there is a continued need to build common understanding of the technical aspects and reporting requirements for monitoring implementation of the Global Plan of Action and assessing the state of the world's FGR.

In parallel with the preparation of this report, FAO developed, in collaboration with the national focal points, a new global information system[26] that makes available the data and information

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[26] For more information www.fao.org/silvagris

submitted by countries. Although the main purpose of this information system is to track progress on implementing the Global Plan of Action, it also offers opportunities for improving FGR management at the national level and enhancing regional collaboration on FGR. The new global information system complements other databases developed and maintained by regional networks and international organizations.

Recommended actions

1. Establish and strengthen national FGR inventories.
2. Develop and maintain national, regional and global FGR information systems.
3. Expand genetic monitoring and characterization systems at the national level.
4. Raise awareness of the importance of FGR at the national and international levels.
5. Further develop the monitoring framework for tracking implementation of the Global Plan of Action (including by providing capacity building for national focal points) and the reporting requirements for assessments of the state of the world's FGR.

13.3 *In situ* and *ex situ* conservation of forest genetic resources

Although progress has been made in conserving FGR since publication of SoW-FGR1, there is still a need in many countries to enhance *in situ* and *ex situ* conservation systems and programmes because of limited coverage in terms of both species and their genetic resources. The *in situ* conservation of trees and other woody plants remains the preferred approach because it maintains evolutionary processes within populations. *Ex situ* conservation complements *in situ* conservation and is an important backup measure, especially when the population size of a species is low in natural habitats or threats to existing populations are large and imminent. In some cases, however, *ex situ* conservation may be the only feasible option for safeguarding FGR.

Countries differ in their understanding of the concept of *in situ* FGR conservation, which hampers implementation of conservation efforts at the national level as well as regional and international cooperation supporting such efforts. Ideally, *in situ* conservation efforts should cover the entire natural distribution of a species, but completeness is difficult to achieve when countries have differing interpretations of the concept. For example, countries that rely on protected areas may not consider that tree populations in other areas (e.g. in degraded forests and agricultural landscapes) are important for genetic conservation, leaving gaps in conservation efforts. Viable populations often exist outside protected areas, especially in managed forests and on farms (*circa situm*). Such populations may be genetically distinct and could be included in genetic conservation programmes and managed in collaboration with local communities and forest owners. An important message to convey is that the genetic conservation of trees and other woody plants does not prevent people from using the resource.

Ex situ conservation could also be better connected to FGR use. In addition to seed storage, planted conservation stands and other live collections, other approaches – such as breeding seedling orchards – allow the better harnessing of *ex situ* conservation for tree breeding and seed production. *Ex situ* conservation can also benefit from an increase in knowledge on the storage behaviour of tree seeds, although boreal and temperate species are better studied in this regard than tropical species, and the global distribution patterns of recalcitrant- and orthodox-seeded species is better known now than at the time of SoW-FGR1. With climate change already affecting many tree populations, *ex situ* conservation programmes should also promote assisted migration, when needed, by establishing conservation stands in climatically more favourable areas and even beyond species' current distribution ranges.

Deforestation and forest fragmentation, climate change and pests and diseases threaten FGR and pose challenges for both *in situ* and *ex situ* conservation. Threat assessment methods have advanced considerably in recent years and should be used more widely, including – in combination with gap analysis – for prioritizing conservation efforts. They should not be used in isolation of real-life realities, however, such as the need to use FGR and the availability of financial and human resources. Thus, priorities for FGR conservation should be defined by combining the results of threat, gap, need and resource assessments.

The regional networks on FGR in Asia (APFORGEN) and Europe (EUFORGEN) have spearheaded the development and implementation of regional conservation strategies to increase coordination among countries and the efficiency of conservation efforts. The importance of such strategies is also recognized in other regions, which, however, have made little progress since SoW-FGR1. Because the natural distribution of many species spans two or more countries, and as climate change increases the interdependence of countries for conserving and using FGR, more action is needed to drive regional strategies on *in situ* and *ex situ* conservation, building on the efforts of existing regional FGR networks and other relevant regional collaboration mechanisms.

Recommended actions

1. Reinforce national *in situ* conservation systems.
2. Strengthen national *ex situ* conservation systems.
3. Analyse gaps in the existing conservation efforts for the establishment of new *in situ* and *ex situ* conservation units.
4. Carry out threat, needs and resource assessments for prioritizing species and populations for *in situ* and *ex situ* conservation.
5. Develop and implement regional *in situ* and *ex situ* conservation strategies to increase coordination and efficiency.

13.4 Sustainable use, development and management of forest genetic resources

Progress on reinforcing national tree-seed programmes has been modest since SoW-FGR1. As a result, many countries are experiencing persistent or periodic shortages of seeds and other forest reproductive material and are struggling to meet demand, even with seed and seedling imports. Many countries reported having limited financial and human resources for running tree-seed programmes. Nevertheless, most countries noted that increasing the supply and quality of forest reproductive material is a high priority. In addition to formal governmental programmes, there is a need to better understand and promote informal tree germplasm supply chains in countries where such supply chains play significant roles. Increasing the production of seeds and other forest reproductive material is crucial for meeting global goals, such as achieving the target of a 3 percent increase in the global forest area by 2030 under GFG 1. Climate change is bringing further challenges, not only for FGR conservation but also for the production and deployment of material, and this needs to be considered when reinforcing national tree-seed programmes and using FGR.

Tree-improvement and tree-breeding programmes have continued in all regions, albeit at differing levels of intensity and investment. Globally, the main focus is on economically important species, and few programmes have advanced beyond the first generation of selection. Most new forests are still being established with unimproved germplasm, so the potential of tree improvement and breeding to enhance productivity and increase adaptation to climate change and resistance to pests and diseases is underused. Research is applying existing and new methodologies for accelerating tree improvement and breeding, and the results should be brought into practice to increase the availability of improved germplasm.

Deforestation, forest degradation, climate change, invasive species, browsing by livestock and wildlife, and the unsustainable harvesting of wood and non-wood products continue to threaten FGR. It is urgent, therefore, to better incorporate genetic aspects into the management of both natural and planted forests to help increase their resilience to climate change and ensure the long-term sustainability of forest management. The appropriate use of FGR in natural and planted forests, including assisted migration, should be promoted. To increase the consideration of genetic aspects in practical forest management, there is a need to develop practical methods for collecting information on FGR as part of regular forest inventories and for incorporating FGR data into forest management planning. The use of appropriate existing and novel technologies should be promoted in the conservation, use and development of FGR.

Recommended actions

1. Reinforce national tree-seed programmes to increase the supply of high-quality and well-documented seed.
2. Strengthen tree-breeding programmes to increase the availability of improved germplasm.
3. Promote the appropriate use of FGR in forestry, including agroforestry and forest restoration.
4. Integrate genetic aspects into the management of natural and planted forests.
5. Promote the use of appropriate existing and novel technologies in FGR management.

13.5 Policies, institutions and capacity building

Several countries have made progress since SoW-FGR1 in strengthening their institutional frameworks for the conservation, use and development of FGR. Many limitations and gaps in institutional frameworks exist, however, not only at the national level but also regionally and globally. A little more than half the reporting countries have national coordination mechanisms on FGR, but these would benefit from broader participation by stakeholders. In other countries, the lack of national coordination mechanisms hinders efforts to improve FGR management and create synergies with other national programmes and initiatives on forests, biodiversity and climate change. The lack of national strategies for FGR makes it difficult to allocate limited resources efficiently when goals, needs and priorities for FGR work have not been identified and agreed among stakeholders.

The management of FGR is also inadequately integrated into national forest policies, national biodiversity strategies and action plans, and national adaptation strategies for climate change. The level of integration into such policies, strategies and action plans varies considerably, from mentions and acknowledgements to specific actions on FGR. As part of future integration efforts, the latter approach should be favoured.

An important area in which progress is limited is the strengthening of educational and research capacities on FGR. The human resources available for FGR management are minimal in many countries and, in some, have declined since SoW-FGR1. Globally, forest education is declining, and there is inadequate coverage of FGR (and other areas of natural resource management) in all regions. There is a need to improve education on FGR, especially at the technical and vocational levels. It is also important to strengthen academic education on FGR to provide the necessary scientific expertise. Research is advancing and the technologies available for FGR management are evolving rapidly; it is crucial, therefore, to provide on-the-job training for agencies and institutions involved in FGR work and to continue extension programmes targeting different stakeholders.

International cooperation on FGR continues actively worldwide. Regional FGR networks and international organizations play important roles in providing technical – and sometimes financial

– support for FGR management at the national level. Regional collaboration is particularly strong in Asia, Europe and North America and should be strengthened in other regions. Academic institutions and international organizations have developed many tools and knowledge products for FGR management, but such outputs are not fully utilized in practical work and need to be better disseminated to stakeholders on the ground.

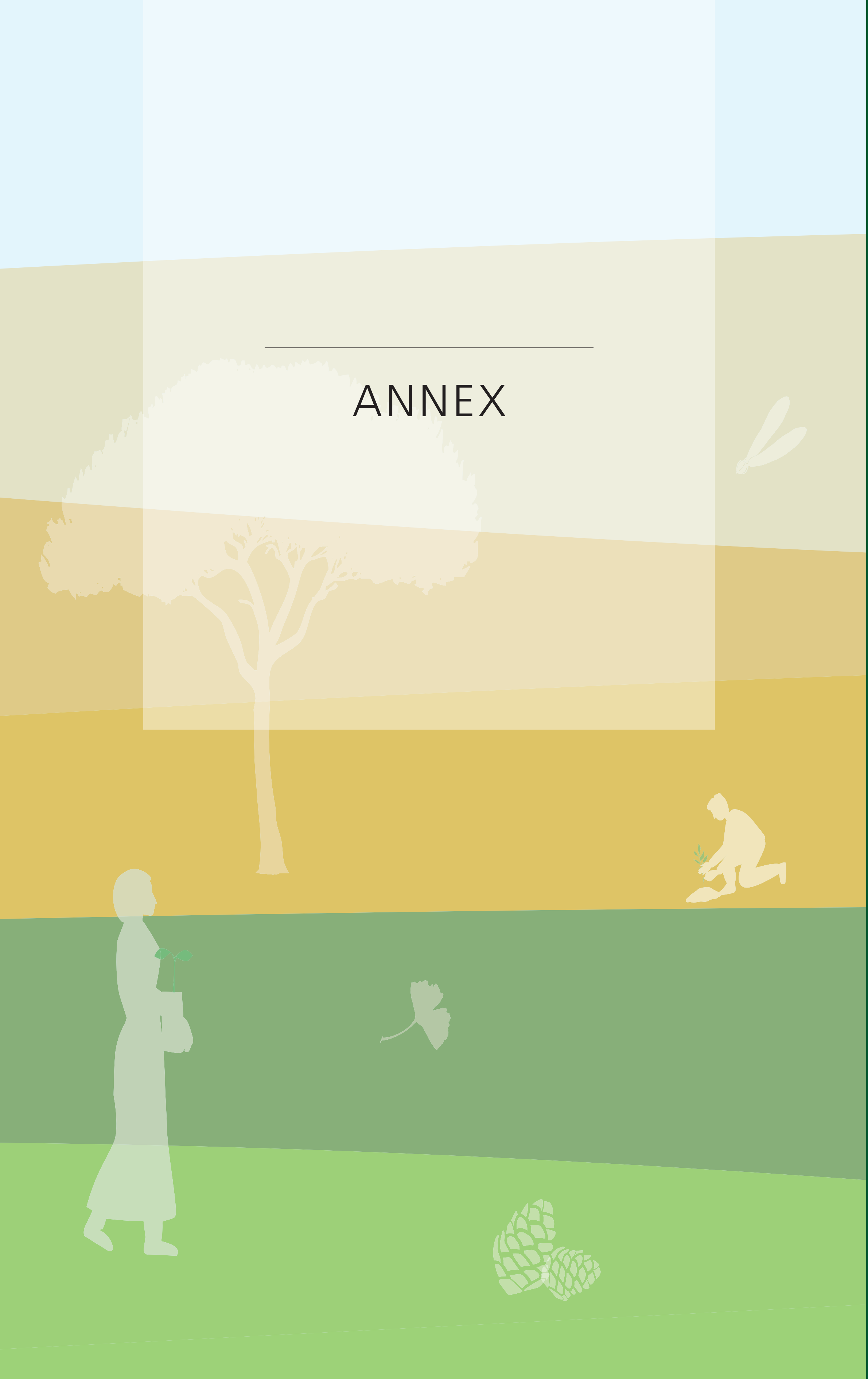
Many countries noted that a lack of adequate long-term funding is a major challenge for FGR conservation, use and development and also hampers the potential of countries to contribute to international cooperation on FGR. Although opportunities exist for mobilizing project- and programme-based funding from multilateral financing mechanisms and donors for FGR work, countries should also consider investing their own public funds, in accordance with their financial situations. Such investments could be allocated to activities such as FGR conservation, national tree-seed programmes, and training, which are less attractive to the private sector. There is also a need for economic analyses of the benefits of FGR conservation and use, as well as of the costs associated with losing FGR, to inform policymaking. Overall, resource mobilization efforts need strengthening at the national and international levels to increase funding for FGR work, particularly in developing countries and countries with economies in transition. These efforts could be based on the funding strategy adopted by the Commission in 2019 for the implementation of the Global Plan of Action (FAO and Commission on Genetic Resources for Food and Agriculture, 2019a).

Recommended actions

1. Establish and strengthen national coordination mechanisms on FGR and promote their cooperation with other relevant national programmes and initiatives.
2. Develop and implement national strategies for FGR conservation, use and development.
3. Promote the integration of FGR management into relevant national policies, strategies and action plans.
4. Strengthen educational, technical and research capacities on FGR.
5. Reinforce international (including regional) cooperation on FGR to support FGR management at the national level and strengthen scientific collaboration.
6. Strengthen efforts at the national, regional and global levels to mobilize financial resources for FGR conservation, use and development.

13.6 Conclusions

The four priority areas of the Global Plan of Action remain highly relevant to the needs and priorities reported by countries. Although progress has been made in each priority area, limitations and gaps still exist that require continued and reinforced action. The findings of this report and the recommended actions provide a starting point for the Intergovernmental Technical Working Group on FGR and the Commission to consider what needs to be done at the national, regional and global levels in the next decade to further improve FGR management. Because FGR underpin the many contributions of forests and trees to people's well-being, sustainable development, biodiversity conservation, and climate-change mitigation and adaptation, it is also important to increase international awareness of the Global Plan of Action.

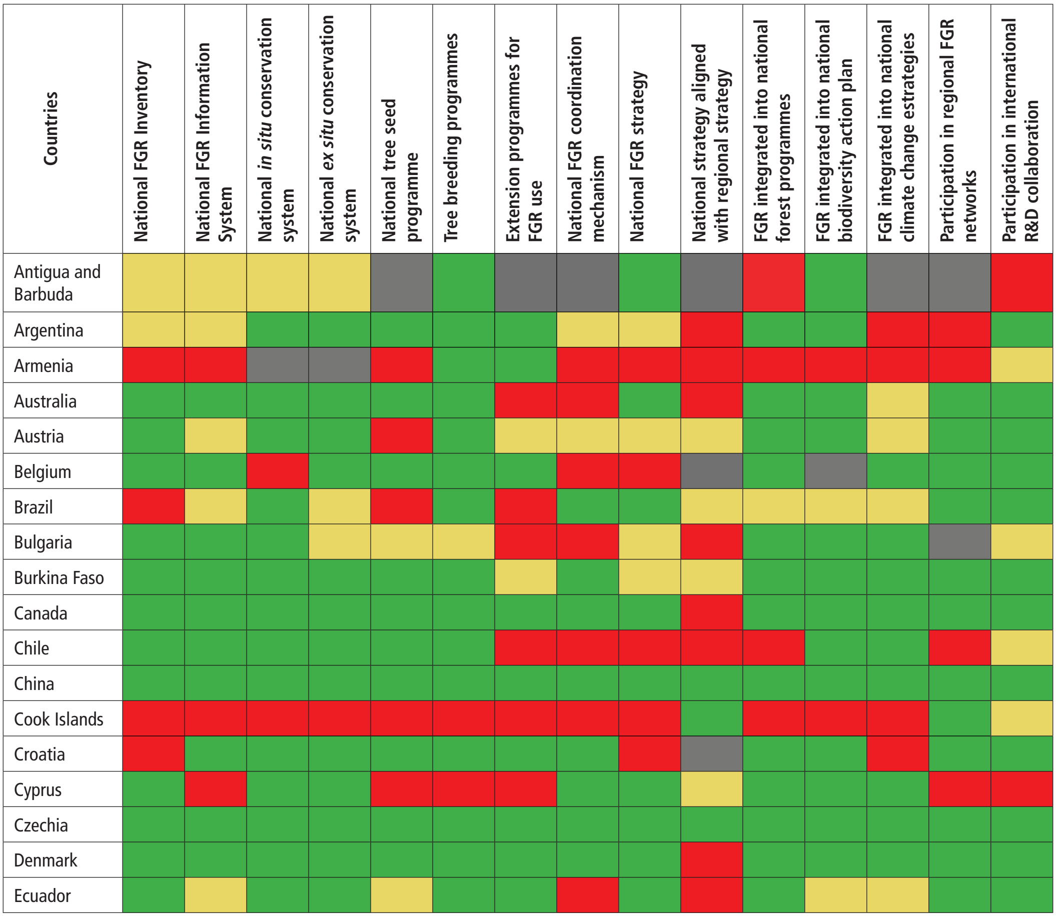


ANNEX

Annex

State of institutional arrangements for the conservation, sustainable use and development of forest genetic resources

🟩 In place 🟨 Initiated 🟥 No ⬛ No information



Countries	National FGR Inventory	National FGR Information System	National *in situ* conservation system	National *ex situ* conservation system	National tree seed programme	Tree breeding programmes	Extension programmes for FGR use	National FGR coordination mechanism	National FGR strategy	National strategy aligned with regional strategy	FGR integrated into national forest programmes	FGR integrated into national biodiversity action plan	FGR integrated into national climate change estrategies	Participation in regional FGR networks	Participation in international R&D collaboration
Antigua and Barbuda	🟨	🟨	🟨	🟨	⬛	🟩	⬛	⬛	🟩	⬛	🟥	🟩	⬛	⬛	🟥
Argentina	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟥	🟩	🟩	🟥	🟥	🟩
Armenia	🟥	🟥	⬛	⬛	🟥	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨
Australia	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟥	🟩	🟩	🟨	🟩	🟩
Austria	🟩	🟨	🟩	🟩	🟥	🟩	🟨	🟨	🟨	🟨	🟩	🟩	🟨	🟩	🟩
Belgium	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟥	🟥	⬛	🟩	⬛	🟩	🟩	🟩
Brazil	🟥	🟨	🟩	🟨	🟥	🟩	🟥	🟩	🟩	🟨	🟨	🟨	🟨	🟩	🟩
Bulgaria	🟩	🟩	🟩	🟨	🟨	🟨	🟥	🟥	🟨	🟥	🟩	🟩	🟩	⬛	🟨
Burkina Faso	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟩
Canada	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩
Chile	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟥	🟨
China	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Cook Islands	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟨
Croatia	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	⬛	🟩	🟩	🟥	🟩	🟩
Cyprus	🟩	🟥	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟨	🟩	🟩	🟩	🟥	🟥
Czechia	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Denmark	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩
Ecuador	🟩	🟨	🟩	🟩	🟨	🟩	🟩	🟥	🟩	🟥	🟩	🟨	🟨	🟩	🟩

Countries	National FGR Inventory	National FGR Information System	National *in situ* conservation system	National *ex situ* conservation system	National tree seed programme	Tree breeding programmes	Extension programmes for FGR use	National FGR coordination mechanism	National FGR strategy	National strategy aligned with regional strategy	FGR integrated into national forest programmes	FGR integrated into national biodiversity action plan	FGR integrated into national climate change estrategies	Participation in regional FGR networks	Participation in international R&D collaboration
El Salvador	🟥	🟥	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨
Estonia	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟥
Eswatini	🟥	🟨	🟥	🟨	🟩	⬛	🟩	🟨	🟥	⬛	🟩	🟩	🟩	🟨	🟨
Ethiopia	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Fiji	🟨	🟨	🟩	🟩	🟩	🟥	🟩	🟥	🟥	🟥	🟨	🟩	🟩	🟩	🟩
Finland	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
France	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Georgia	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟩	🟨	🟥	🟨
Germany	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟩	🟩
Greece	🟥	🟥	🟩	🟩	🟩	⬛	⬛	🟥	🟥	⬛	⬛	⬛	⬛	🟩	🟩
Guatemala	🟩	🟩	🟨	🟨	🟨	🟩	🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟨
Guinea	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Hungary	🟩	🟩	🟨	🟩	🟩	🟩	🟥	🟩	🟩	🟥	🟩	🟥	🟥	🟩	🟩
Iceland	🟩	🟨	🟩	🟥	🟩	🟩	🟩	🟩	🟨	⬛	🟥	🟥	🟥	🟩	🟩
India	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Indonesia	🟩	🟥	🟩	🟩	🟥	🟩	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟨	🟨
Iran (Islamic Republic of)	🟨	🟨	🟨	🟩	🟩	🟩	🟨	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥
Ireland	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟨	🟩	🟩
Italy	🟩	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Japan	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩
Kenya	🟥	🟥	🟩	🟩	🟩	🟥	🟩	🟥	🟩	🟥	🟩	🟩	🟩	🟩	🟩
Lao People's Democratic Republic	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨
Lebanon	🟥	🟥	🟩	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟥	🟩	🟩
Lithuania	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟥	🟩	🟥	🟥	🟩	🟩
Luxembourg	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨
Madagascar	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟥	🟩	🟩	🟥	🟩	🟩
Malaysia	🟩	🟩	⬛	⬛	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Mali	🟨	⬛	🟨	🟩	🟩	🟩	🟩	🟩	⬛	🟩	🟩	🟩	🟩	🟩	🟩
Malta	🟩	🟩	🟩	🟨	🟨	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Mauritania	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟩	🟥	🟥	🟨

Countries	National FGR Inventory	National FGR Information System	National *in situ* conservation system	National *ex situ* conservation system	National tree seed programme	Tree breeding programmes	Extension programmes for FGR use	National FGR coordination mechanism	National FGR strategy	National strategy aligned with regional strategy	FGR integrated into national forest programmes	FGR integrated into national biodiversity action plan	FGR integrated into national climate change estrategies	Participation in regional FGR networks	Participation in international R&D collaboration
Mexico	🟥	⬛	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟨	🟩	🟨	🟩	🟩
Morocco	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟥	🟨	🟩	🟩	🟨	🟩
Namibia	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟨	🟩	🟩
Netherlands	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟥	🟥	🟥	🟥	🟩	🟩
Niger	🟩	🟩	🟩	🟩	🟨	⬛	🟩	🟨	🟩	🟩	🟩	🟩	🟨	🟩	🟨
Nigeria	🟥	🟨	🟩	🟩	🟩	🟩	🟨	⬛	🟥	⬛	🟩	🟩	🟩	🟨	🟨
Norway	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Panama	⬛	🟩	🟩	⬛	🟩	🟩	🟩	🟨	⬛	⬛	🟥	🟩	⬛	⬛	🟥
Peru	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟩
Poland	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	⬛	🟨	🟩	🟩	🟩	🟨
Portugal	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	⬛	🟩	🟩	🟥	🟨	🟥
Republic of Korea	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Russian Federation	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟨	🟩	🟨	🟨	🟩
Saint Lucia	🟥	🟥	🟩	🟨	🟥	🟥	🟥	🟥	🟨	🟥	🟩	🟩	🟨	🟩	🟩
Serbia	🟩	🟨	🟩	🟩	⬛	🟩	🟥	🟩	🟩	⬛	🟨	🟩	🟥	🟩	🟩
Slovenia	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	⬛	🟩	🟩
South Africa	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	⬛	🟩	🟩	🟩	🟩	🟩
Spain	🟩	🟩	🟩	🟨	🟩	🟩	🟨	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩
Sri Lanka	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟥	🟥	🟩	🟩	🟩	🟩	🟨
Sweden	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩
Switzerland	🟩	🟨	🟩	🟩	🟩	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩
Thailand	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	⬛	⬛	🟩	🟩	🟥	🟩	🟩
Türkiye	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Ukraine	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟩	🟨	🟨	🟨	🟨
United Kingdom	🟨	🟨	🟩	🟩	🟨	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩
United States of America	🟩	🟩	⬛	🟥	🟥	🟩	🟩	⬛	🟩	🟩	🟥	🟥	🟩	🟩	🟩
Vanuatu	🟥	🟥	🟥	🟥	🟨	🟥	🟩	🟥	🟩	🟥	🟩	🟨	🟥	🟥	🟩
Yemen	🟩	🟨	🟩	🟩	🟨	⬛	🟩	🟩	🟩	🟩	🟥	🟩	🟨	🟩	🟩
Zimbabwe	🟩	🟨	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩

References

Adu-Gyamfi, R., Wetten, A. & Rodríguez López, C.M. 2016. Effect of cryopreservation and post-cryopreservation somatic embryogenesis on the epigenetic fidelity of cocoa (*Theobroma cacao* L.). *PLoS One*, 11: e0158857. doi: 10.1371/journal.pone.0158857

Adu-Gyamfi, R., Wetten, A., Adu-Gyamfi, R. & Wetten, A. 2020. Cocoa (*Theobroma cacao* L.) somatic embryos tolerate some ice crystallization during cryopreservation. *Agric Sci*, 11: 223–234. doi: 10.4236/AS.2020.113014

Aguilar, R., Ashworth, L., Galetto, L. & Aizen, M.A. 2006. Plant reproductive susceptibility to habitat fragmentation: review and synthesis through a meta-analysis. *Ecology Letters*, 9(8): 968–980. doi: 10.1111/j.1461-0248.2006.00927.x

Ahmar, S., Ballesta, P., Ali, M. & Mora-Poblete, F. 2021. Achievements and challenges of genomics-assisted breeding in forest trees: from marker-assisted selection to genome editing. *International Journal of Molecular Sciences*, 22(19): 10583. doi: 10.3390/ijms221910583

Ahossou, O.D., Daïnou, K., Janssens, S.B., Triest, L. & Hardy, O.J. 2020. Species delimitation and phylogeography of African tree populations of the genus Parkia (Fabaceae). *Tree Genetics & Genomes*, 16(5): 68. doi: 10.1007/s11295-020-01463-x

Ahuja, M.R. 2017. Climate change, genetic diversity, and conservation of paleoendemic redwoods. *In* M.R. Ahuja & S.M. Jain, eds. *Biodiversity and conservation of woody plants*, pp. 69–93. Cham, Switzerland, Springer. doi: 10.1007/978-3-319-66426-2

Ahuja, M.R. 2021. Fate of forest tree biotechnology facing climate change. *Silvae Genetica*, 70(1): 117–136. doi: 10.2478/sg-2021-0010

Aitken, S.N., Yeaman, S., Holliday, J.A., Wang, T. & Curtis-McLean, S. 2008. Adaptation, migration or extirpation: climate change outcomes for tree populations. *Evolutionary Applications*, 1(1): 95–111. doi: 10.1111/j.1752-4571.2007.00013.x

Aitken, S.N. & Whitlock, M.C. 2013. Assisted gene flow to facilitate local adaptation to climate change. *Annual Review of Ecology, Evolution, and Systematics*, 44(1): 367–388. doi: 10.1146/annurev-ecolsys-110512-135747

Aitken, S.N. & Bemmels, J.B. 2015. Time to get moving: assisted gene flow of forest trees. *Evolutionary Applications*, 9(1): 271–290. doi: 10.1111/eva.12293

Aitken, S.N. & Whitlock, M.C. 2013. Assisted gene flow to facilitate local adaptation to climate change. *Annual Review of Ecology, Evolution, and Systematics*, 44(1): 367–388. DOIdoi: 10.1146/annurev-ecolsys-110512-135747

Alberto, F.J., Aitken, S.N., Alía, R., González-Martínez, S.C., Hänninen, H., Kremer, A., Lefèvre, F. *et al*. 2013. Potential for evolutionary responses to climate change–evidence from tree populations. *Global Change Biology*, 19(6): 1645–1661. doi: 10.1111/gcb.12181

Aleman, J.C. & Staver, A.C. 2018. Spatial patterns in the global distributions of savanna and forest. *Global Ecology and Biogeography*, 8: 1-12. doi: 10.1111/geb.12739

Alfaro, R.I., Fady, B., Vendramin, G.G., Dawson, I.K., Fleming, R.A., Sáenz-Romero, C., Lindig-Cisneros, R.A. *et al*. 2014. The role of forest genetic resources in responding to biotic and abiotic factors in the context of anthropogenic climate change. *Forest Ecology and Management*, 333: 76–87. doi :10.1016/j.foreco.2014.04.006

Aliyu, O.M. 2005. Application of tissue culture to cashew (*Anacardium occidentale* L.) breeding: an appraisal. *Afr. J. Biotechnol.*, 4: 1485–1489.

Alkama, R. & Cescatti, A. 2016. Biophysical climate impacts of recent changes in global forest cover. *Science*, 351(6273): 600–604. doi: 10.1126/science.aac8083

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kizberger, T. *et al*. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management*, 259(4): 660–684. doi: 10.1016/j.foreco.2009.09.001

Angelsen, A., Martius, C., de Sy, V. & Duchelle, A. 2018. *Transforming REDD+ – Lessons and new directions*. Bogor, Indonesia, Center for International Forestry Research. 276 p.

APFORGEN (Asia Pacific Forest Genetic Resources Programme). 2023. Strategy 2023-2030: Conserving, restoring, and sustainably managing forest and tree genetic resources in Asia and the Pacific. APFORGEN and Bioversity International. https://www.apforgen.org/about/strategy-2023-2030

APFORGEN. 2024. Strengthening Seed Supply. Project website. Asia-Pacific Forest Genetic Resources Programme (APFORGEN). https://www.apforgen.org/initiatives/strengthening-seed-supply.

Apps, M. J., Kurz, W. A., Luxmoore, R. J., Nilsson, L. O., Sedjo, R. A., Schmidt, R. *et al.* 1993. Boreal forests and tundra. *Water, Air, and Soil Pollution*, 70: 39–53.

Aravanopoulos, F.A., Tollefsrud, M.M., Graudal, L., Koskela, J., Kätzel, R., Soto, A., *et al*. 2015. Genetic monitoring methods for genetic conservation units of forest trees in Europe. European Forest Genetic Resources Programme (EUFORGEN). Rome, Bioversity International.

Aravanopoulos, F.A. 2016. Conservation and monitoring of tree genetic resources in temperate forests. *Current Forestry Reports*, 2(2): 119–129. doi: 10.1007/s40725-016-0038-8

Arbeloa, A., Marín, J. A., Andreu, P., García, E. & Lorente, P. 2015. *In vitro* conservation of fruit trees by slow growth storage. In: *VI International Symposium on Production and Establishment of Micropropagated Plants*, *1155*: 101-106.

Arenas, S., Cortés, A.J., Mastretta-Yanes, A. & Jaramillo-Correa, J.P. 2021. Evaluating the accuracy of genomic prediction for the management and conservation of relictual natural tree populations. *Tree Genetics & Genomes*, 17(1): 1–19. doi: 10.1007/s11295-020-01489-1

Arif, M.A.R., Afzal, I. & Börner, A. 2022. Genetic aspects and molecular causes of seed longevity—a review. *Plants*, 11: 598. doi: 10.3390/plants11050598

Ariyadasa, K.P. 2002. *Assessment of tree resources in the homegardens of Sri Lanka*. FAO Regional Office for Asia and Pacific, Bangkok, Thailand.

Ash, J.D., Givnish, T.J. & Waller D.M. 2017. Tracking lags in historical plant species' shifts in relation to regional climate change. *Global Change Biology*, 23(3): 1305–1315. doi: 10.1111/gcb.13429

Ashton, P. & Zhu, H. 2020. The tropical-subtropical evergreen forest transition in East Asia: An exploration. *Plant Diversity*, 42: 255–280. doi: 10.1016/j.pld.2020.04.001

Ashwath, M.N., Lavale, S.A., Santhoshkumar, A.V., Mohapatra, S.R., Bhardwaj, A., Dash, U., Shiran, K. *et al*. 2023. Genome-wide association studies: an intuitive solution for SNP identification and gene mapping in trees. *Functional & Integrative Genomics*, 23(4): 297. doi: 10.1007/s10142-023-01224-8

Attigala, L.R., Kaththriarachchi, H. & Clark, L.G. 2016. Taxonomic revision of the temperate woody bamboo genus *Kuruna* (Poaceae: Bambusoideae: Arundinarieae). *Systematic Botany,* 41. doi: 10.1600/036364416X690570

Azarkovich, M.I. 2016. Stress-induced proteins in recalcitrant seeds during deep dormancy and early germination. *Abiotic Biot Stress Plants – Recent Adv Futur Perspect.* doi: 10.5772/61958

Azpilicueta, M. M., Marchelli, P., & Gallo, L. A. 2009. The effects of Quaternary glaciations in Patagonia as evidenced by chloroplast DNA phylogeography of Southern beech *Nothofagus obliqua*. *Tree Genetics & Genomes*, 5: 561–571. doi: 10.1007/s11295-009-0209-x

Azpilicueta, M.M., Marchelli, P., Gallo, L.G., Umana, F., Thomas, E., van Zonneveld, M., Aparicio, A.G. *et al.* 2016. *Zonas genéticas de raulí y roble pellín en Argentina: Herramientas para la conservación y el manejo de la diversidad genética*. Bariloche, Argentina, Instituto Nacional de Tecnología Agropecuaria (INTA). https://hdl.handle.net/10568/88089

Backs, J.R. & Ashley, M.V. 2021. Quercus conservation genetics and genomics: Past, present, and future. *Forests*, 12(7): 882. doi: 10.3390/f12070882

Bajc, M., Aravanopoulos, F., Westergren, M., Fussi, B., Kavaliauskas, D., Alizoti, P., Kiourtsis, F. & Kragher, H. eds. 2020. *Manual for forest genetic* *monitoring*. Slovenian Forestry Institute, Silva Slovenica Publishing Centre. doi: 10.20315/SFS.167

Baker, W.J., Barfod, A.S., Cámara-Leret, R., Dowe, J.L., Heatubun, C.D., Petoe, P., Turner, J.H. *et al.* 2024. *Palms of New Guinea*. Kew, UK, Royal Botanic Gardens.

Balkenhol, N., Dudaniec, R.Y., Krutovsky, K.V., Johnson, J.S., Cairns, D.M., Segelbacher, G., Selkoe, K.A. *et al*. 2017. Landscape genomics: understanding relationships between environmental heterogeneity and genomic characteristics of populations. In: O. Rajora, ed. *Population genomics,* pp. 261–322. Cham, Switzerland, Springer. doi: 10.1007/13836_2017_2

Ballesteros, D. & Pritchard, H.W. 2020. The cryobiotechnology of oaks: an integration of approaches for the long-term ex situ conservation of Quercus species. *Forests*, 11: 1281. doi: 10.3390/f11121281

Bamboo Biodiversity. 2023. https://www.eeob.iastate.edu/research/bamboo/maps.html. [Cited 15 Feb 2023].

Banik, R.L. 2015. Bamboo silviculture. In: W. Liese & M. Koehl, eds. *Bamboo, the plant and its uses*, pp. 113–174. Heidelberg, Germany, Springer Verlag, Tropical Forestry Series.

Baral, H.O., Queloz, V. & Hosoya, T. 2014. *Hymenoscyphus fraxineus*, the correct scientific name for the fungus causing ash dieback in Europe. *IMA fungus*, 5(1): 79–80. doi: 10.5598/imafungus.2014.05.01.09

Barnes, R.D. 1995. The breeding seedling orchard in the multiple population breeding strategy. *Silvae Genetica*, 44: 81–88.

Barra-Jiménez, A., Aronen, T.S., Alegre, J. & Toribio, M. 2015. Cryopreservation of embryogenic tissues from mature holm oak trees. *Cryobiology*, 70: 217–225. doi: 10.1016/j.cryobiol.2015.02.006

Barstow, M., Boshier, D., Bountithiponh, C., Changtragoon, S., Gaisberger, H., Hartvig, I., Hung, H. *et al.* 2022a. *Dalbergia cochinchinensis. The IUCN Red List of Threatened Species 2022*: e.T215342548A2822125. doi: 10.2305/IUCN.UK.2022-1.RLTS.T215342548A2822125.en

Barstow, M., Boshier, D., Bountithiponh, C., Changtragoon, S., Gaisberger, H., Hartvig, I., Hung, H. *et al.* 2022b. *Dalbergia oliveri. The IUCN Red List of Threatened Species 2022*: e.T215341339A2813403. doi: 10.2305/IUCN.UK.2022-1.RLTS.T215341339A2813403.en

Bartholomé, J., Brachi, B., Marçais, B., Mougou-Hamdane, A., Bodénès, C., Plomion, C., Robin, C. & Desprez-Loustau, M.L. 2020. The genetics of exapted resistance to two exotic pathogens in pedunculate oak. *New Phytologist*, 226(4): 1088–1103. doi: 10.1111/nph.16319

Bayala, J., Kindt, R., Belem, M. & Kalinganire, A. 2011. Factors affecting the dynamics of tree diversity in agroforestry parklands of cereal and cotton farming systems in Burkina Faso. *New Forests*, 41: 281-296. doi:10.1007/s11056-010-9222-z

BCGI. 2023. The global tree assessment. Conservation assessments for all the world's tree species. Botanic Gardens Conservation International, Kew, UK. https://www.bgci.org/our-work/networks/gta/

Becerra-Vázquez, Á.G., Sánchez-Nieto, S., Coates, R. *et al.* 2018. Seed longevity of five tropical species from south-eastern Mexico: changes in seed germination during storage. *Trop Conserv Sci*, 11: 1–17. doi: 10.1177/1940082918779489

Beech, E., Rivers, M., Oldfield, S. & Smith, P.P. 2017. GlobalTreeSearch: The first complete global database of tree species and country distributions. *Journal of Sustainable Forestry*, 36(5): 454–489. doi: 10.1080/10549811.2017.1310049

Beech, E., Rivers, M., Rabarimanarivo, M., Ravololomanana, N., Manjato, N., Lantoarisoa, F., Andriambololonera, S. *et al.* 2021. *Red List of Trees of Madagascar*. Richmond, UK, BGCI.

Beech, E., Hills, R. & Rivers, M. 2022. GlobalTree Portal: visualizing the state of the world's trees. *Oryx*, 56(3): 332–332. doi: 10.1017/S0030605322000254

Benelli, C., De Carlo, A. & Engelmann, F. 2013. Recent advances in the cryopreservation of shoot-derived germplasm of economically important fruit trees of Actinidia, Diospyros, Malus, Olea, Prunus, Pyrus and Vitis. *Biotechnol Adv*, 31: 175–185. doi:10.1016/j.biotechadv.2012.09.004

Benestan, L.M., Ferchaud, A.L., Hohenlohe, P.A., Garner, B.A., Naylor, G.J., Baums, I.B., Schwartz, M.K. *et al.* 2016. Conservation genomics of natural and managed populations: building a conceptual and practical framework. *Molecular Ecology*, 25(13): 2967–2977. doi: 10.1111/mec.13647

Benito Garzón, M., Robson, T.M. & Hampe, A. 2019. ΔTrait SDMs: species distribution models that account for local adaptation and phenotypic plasticity. *New Phytologist*, 222(4): 1757–1765. doi: 10.1111/nph.15716

Benton, A. 2015. Chapter 2, Priority species of bamboo. In: W. Liese & M. Koehl, eds. *Bamboo, the plant and its uses*, pp. 31–41. Heidelberg, Germany, Springer Verlag, Tropical Forestry Series.

Berjak, P. & Pammenter, N.W. 2017. Recalcitrance. In: *Encycl. Appl. Plant Sci.*, 1: 532–539.

Bewg, W.P., Ci, D. & Tsai, C.-J. 2018. Genome editing in trees: from multiple repair pathways to long-term stability. *Front Plant Sci*, 9: 1732. doi:10.3389/fpls.2018.01732

BGCI (Botanic Gardens Conservation International). 2021. *State of the world's trees*. Richmond, UK. https://www.bgci.org/wp/wp-content/uploads/2021/08/FINAL-GTAReportMedRes-1.pdf

BGCI. 2024a. *GlobalTreeSearch online database*. Richmond, UK. www.bgci.org [Cited 30 May 2024].

BGCI. 2024b. *GlobalTree Portal online database.* Richmond, UK. https://www.bgci.org/resources/bgci-databases/globaltree-portal/ [Cited 30 May 2024].

Bian, L., Zhang, H., Ge, Y., Čepl, J., Stejskal, J. & EL-Kassaby, Y.A. 2022. Closing the gap between phenotyping and genotyping: review of advanced, image-based phenotyping technologies in forestry. *Annals of Forest Science*, 79(1): 1–21. doi: 10.1186/s13595-022-01143-x

Bilodeau, P., Roe, A.D., Bilodeau, G., Blackburn, G.S., Cui, M., Cusson, M., Doucet, D. *et al*. 2019. Biosurveillance of forest insects: part II—adoption of genomic tools by end user communities and barriers to integration. *Journal of Pest Science*, 92(1): 71–82. doi: 10.1007/s10340-018-1001-1

Blanc-Jolivet, C., Yanbaev, Y., Kersten, B. & Degen, B. 2018. A set of SNP markers for timber tracking of *Larix* spp. in Europe and Russia. *Forestry*, 91: 614–628. doi:10.1093/forestry/cpy020

Booth, T.H., Broadhurst, L.M., Pinkard, E., Prober, S.M., Dillon, S.K., Bush, D., Pinyopusarerk, K. *et al.* 2015. Native forests and climate change: Lessons from eucalypts. *Forest Ecology and Management*, 347: 18–29. doi: 10.1016/j.foreco.2015.03.002

Borrell, J. S., Zohren, J., Nichols, R. A. & Buggs, R. J. A. 2020. Genomic assessment of local adaptation in dwarf birch to inform assisted gene flow. *Evolutionary Applications*, 13: 161–175. doi: 10.1111/eva.12883

Boshier, D. H., Gordon, J. E. & Barrance, A. J. 2004. Prospects for *Circa Situm* tree conservation in mesoamerican dry-forest agro-ecosystems. In: *Biodiversity conservation in Costa Rica: Learning the lessons in a seasonal dry forest,* pp. 210–226. Oakland, USA, University of California Press. doi: 10.1525/california/9780520223097.003.0016

Bouka, G.U., Doumenge, C., Ekué, M.R., Daïnou, K., Florence, J., Degen, B., Loumetu, J.A. *et al.* 2022. *Khaya* revisited: Genetic markers and morphological analysis reveal six species in the widespread taxon *K. anthotheca. Taxon*, 71(4): 814–832. doi: 10.1002/tax.12720

Bower, A., Devine, W. & Aubry, C. 2017. Climate change and forest trees in the Pacific Northwest: a vulnerability assessment and recommended actions for national forests. In: R.A. Sniezko, G. Man, V. Hipkins, K. Woeste, D. Gwaze, J.T. Kliejunas *et al.,* eds. 2017. *Proceedings of Workshop on Gene Conservation of Tree Species–Banking on the Future*. Portland, USA, US Department of Agriculture, Forest Service, Pacific Northwest Research Station. https://www.fs.usda.gov/treesearch/pubs/55062

Bradbury, D., Binks, R.M. & Byrne, M. 2021. Genomic data inform conservation of rare tree species: clonality, diversity and hybridity in Eucalyptus series in a global biodiversity hotspot. *Biodiversity and Conservation*, 30(3): 619–641. doi: 10.1007/s10531-020-02106-2

Brandt, M., Tucker, C. J., Kariryaa, A., Rasmussen, K., Abel, C., Small, J., Chave, J. *et al*. 2020. An unexpectedly large count of trees in the West African Sahara and Sahel. *Nature*, 587: 78-82. doi: 10.1038/s41586-020-2824-5

Brazilian Development Bank. 2024. Nota de Técnica Anual do FNRB – Exercício de 2023. Nota Técnica AF/DEPOL nº 019/2024. [Cited 13 January 2025].

Breed, M.F., Stead, M.G., Ottewell, K.M., Gardner M. G. & Lowe A.J. 2013. Which provenance and where? Seed sourcing strategies for revegetation in a changing environment. *Conservation Genetics,* 14: 1–10. doi: 10.1007/s10592-012-0425-z

Breed, M.F., Ottewell, K.M., Gardner, M.G., Marklund, M.H., Dormontt, E.E. & Lowe, A.J. 2015. Mating patterns and pollinator mobility are critical traits in forest fragmentation genetics. *Heredity*, 115(2): 108–114. doi: 10.1038/hdy.2013.48

Brendel, O., Le Thiec, D., Scotti-Saintagne, C., Bodénès, C., Kremer, A. & Guehl, J. M. 2008. Quantitative trait loci controlling water use efficiency and related traits in *Quercus robur* L. *Tree Genetics & Genomes*, 4: 263–278. doi: 10.1007/s11295-007-0107-z

Broadhurst, L. & Boshier, D.H. 2014. Seed provenance for restoration and management: conserving evolutionary potential and utility. In: M. Bozzano, R. Jalonen, E. Thomas, D. Boshier, L. Gallo, S. Cavers, S. Bordács, P. Smith & J. Loo, eds. *Genetic considerations in ecosystem restoration using native tree species*, p. 27–38 State of the World's Forest Genetic Resources – Thematic Study. Rome, FAO, and Bioversity International. https://openknowledge.fao.org/server/api/core/bitstreams/17de727e-5fd3-4b8f-b444-678eeec3d4c5/content

Broadhurst, L., Breed, M., Lowe, A., Bragg, J., Catullo, R., Coates, D. *et al.* 2017. Genetic diversity and structure of the Australian flora. *Diversity and Distributions*, 23(1): 41–52. doi: 10.1111/ddi.12505

Brodde, L., Adamson, K., Camarero, J.J., Castaño, C., Drenkhan, R., Lehtijärvi, A., Luchi, N. *et al*. 2019. Diplodia tip blight on its way to the north: Drivers of disease emergence in northern Europe. *Frontiers Plant Science*, 9: 1818. doi: 10.3389/fpls.2018.01818

Brown, A.H.D. 1989. Core collections: a practical approach to genetic resources management. *Genome*, 31(2): 818–824. doi: 10.1139/g89-144

Bruenig, E.F. 2017. *Conservation and management of tropical rainforests: an integrated approach to sustainability*. 2nd edition. Wallingford, UK, CABI. doi: 10.1079/9781780641409.00

Bruijnzeel, L. A. & Veneklaas, E. J. 1998. Climatic conditions and tropical montane forest productivity: the fog has not lifted yet. *Ecology*, 79: 3–9. doi: 10.2307/176859

Brummitt, N., Araújo, A.C. & Harris, T. 2021. Areas of plant diversity—What do we know? *Plants, People, Planet*, 3: 33–44. doi: 10.1002/ppp3.10110

Bryant, N.D., Pu, Y., Tschaplinski, T.J., Tuskan, G.A., Muchero, W., Kalluri, U.C., Kalluri, U. *et al*. 2020. Transgenic poplar designed for biofuels. *Trends in Plant Science*, 25(9): 881–896. doi: 10.1016/j.tplants.2020.03.008

Buck, J.M., Adams, R.S., Cone, J., Conkle, M.T., Libby, W.J., Eden, C.J. & Knight, M.J. 1970. *California tree seed zones.* San Francisco, USA, California Region, Forest Service, US Department of Agriculture. https://www.fs.usda.gov/psw/publications/conkle/psw_1970_conkle001_buck.pdf

Budde, K.B., Nielsen, L.R., Ravn, H.P. & Kjær, E.D. 2016. The natural evolutionary potential of tree populations to cope with newly introduced pests and pathogens—Lessons learned from forest health catastrophes in recent decades. *Current Forestry Reports*, 2: 18–29. doi: 10.1007/s40725-016-0029-9

Burgarella, C., Barnaud, A., Kane, N.A., Jankowski, F., Scarcelli, N., Billot, C., Vigouroux, Y. & Berthouly-Salazar, C. 2019. Adaptive introgression: an untapped evolutionary mechanism for crop adaptation. *Frontiers in Plant Science*, 10: 4. doi: 10.3389/fpls.2019.00004

Burkill, I.H. 1966. *A dictionary of the economic products of the Malay Peninsula*. 2nd printing. Kuala Lumpur: Ministry of Agriculture and Cooperative.

Burley, J. 2004. A historical overview of forest tree improvement. In: J. Burley, J. Evans & J.A. Youngquist, eds. *Encyclopedia of forest sciences*, pp. 1532–1538. Cambridge, USA, Academic Press. doi: 10.5860/choice.42-1941

Burns, R.M. and B.H. Honkala. 1990. *Silvics of North America, Vol. 1, Conifers.* Washington DC: U.S.D.A. Forest Service Agriculture Handbook 654. **https://www.srs.fs.usda.gov/pubs/misc/ag_654_vol1.pdf** [Cited 30 September 2024].

Byrne, M., Yeates, D. K., Joseph, L., Kearney, M., Bowler, J., Williams, M. A. *et al.* 2008. Birth of a biome: insights into the assembly and maintenance of the Australian arid zone biota. *Molecular Ecology*, 17: 4398–417. doi: 10.1111/j.1365-294x.2008.03899.x

Ćalić, I., Koch, J., Carey, D., Addo-Quaye, C., Carlson, J.E. & Neale, D.B. 2017. Genome-wide association study identifies a major gene for beech bark disease resistance in American beech (*Fagus grandifolia* Ehrh.). *BMC Genomics*, 18(1): 547. doi:10.1186/s12864-017-3931-z

Camara, B., Gosme, M., Ngom, D., Gomis, Z. D., Badji, M., Sanogo, D. & Dupraz, C. 2019. Ecological characterization and evolution of *Elaeis guineensis* Jacq. traditional parklands in Lower Casamance (Senegal). *Agroforestry Systems*, 93: 1251–1260. doi:10.1007/s10457-018-0237-3

Camcore (Central America and Mexico Coniferous Resources Cooperative). 2024. *Camcore home page.* Raleigh, USA, North Carolina State University. https://camcore.cnr.ncsu.edu/

Canavan, S., Richardson, D.M., Visser, V., Le Roux, J.J., Vorontsova, M.S. & Wilson, J.R. 2016. The global distribution of bamboos: assessing correlates of introduction and invasion. *AoB Plants*, 9: plw078. doi: 10.1093/aobpla/plw078

Carbajal-Navarro. A., Navarro-Miranda, E., Blanco-García, A., Cruzado-Vargas, A.L., Gómez-Pineda, E., Zamora-Sánchez, C., Pineda-García F. *et al*. 2019. Ecological restoration of *Abies religiosa* forests using nurse plants and assisted migration in the Monarch Butterfly Biosphere Reserve, Mexico. *Frontiers in Ecology and Evolution*, 7(421): 1–16. https://www.frontiersin.org/articles/10.3389/fevo.2019.00421/full

Carney, J. & Elias, M. 2014. Gendered knowledge and the African shea-nut tree. In: S.B. Hecht, K.D. Morrison & C. Padoch, eds. *The social lives of forests: past, present, and future of woodland resurgence*, pp. 231–238. Chicago, USA, University of Chicago Press. doi: 10.7208/chicago/9780226024134.003.0020

Carvalho, A.L. de, Nelson, B.W., Bianchini, M.C., Plagnol, D., Kuplich, T.M. & Daly, D.C. 2013. Bamboo-dominated forests of the south-west Amazon: Detection, spatial extent, life cycle length and flowering waves. *PLoS ONE*, 8(1): e54852. doi: 10.1371/journal.pone.0054852

Casasoli, M., Derory, J., Morera-Dutrey, C., Brendel, O., Porth, I., Guehl, J.M., Villani, F. & Kremer, A. 2006. Comparison of quantitative trait loci for adaptive traits between oak and chestnut based on an expressed sequence tag consensus map. *Genetics*, 172(1): 533–546. doi: 10.1534/genetics.105.048439

Castellanos-Acuña, D., Lindig-Cisneros, R.A. & Sáenz-Romero, C. 2015. Altitudinal assisted migration of Mexican pines as an adaptation to climate change. *Ecosphere*, 6(1): 1–16. doi: 10.1890/ES14-00375.1

Castellanos-Acuña, D., Vance-Borland, K.W., St. Clair, J.B., Hamann, A., López-Upton, J., Gómez-Pineda, E., Ortega-Rodríguez, J.M. & Sáenz-Romero, C. 2018. Climate-based seed zones for Mexico: guiding reforestation under observed and projected climate change. *New Forests*, 49(3): 297–309. doi: 10.1007/s11056-017-9620-6

Catullo, R.A., Ferrier, S. & Hoffmann, A.A. 2015. Extending spatial modelling of climate change responses beyond the realized niche: estimating, and accommodating, physiological limits and adaptive evolution. *Global Ecology and Biogeography*, 24(10): 1192–1202. doi: 10.1111/geb.12344

Cavender, N., Westwood, M., Bechtoldt, C., Donnelly, G., Oldfield, S., Gardner, M., Rae, D. & McNamara, W. 2015. Strengthening the conservation value of *ex situ* tree collections. *Oryx*, 49: 416–424. doi: 10.1017/s0030605314000866

Cavers, S. & Cottrell, J.E. 2015. The basis of resilience in forest tree species and its use in adaptive forest management in Britain. *Forestry: An International Journal of Forest Research*, 88(1): 13–26. doi: 10.1093/forestry/cpu027

Cazzolla Gatti, R., Reich, P.B., Gamarra, J.G.P., Crowther, T., Hui, C., Morera, A., Bastin, J.F. *et al.* 2022. The number of tree species on Earth. *Proceedings of the National Academy of Sciences*, 119(6): e2115329119. doi: 10.1073/pnas.2115329119

CBD (Convention on Biological Diversity). 2010. *The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets*. Tenth Meeting of the Conference of the Parties to the Convention on Biological Diversity, Nagoya, Japan, 18–29 October 2010. UNEP/CBD/COP/DEC/X/2.

CBD. 2022. Draft decisions for the fifteenth meeting of the Conference of the Parties to the Convention on Biological Diversity. CBD/COP/15/2. United Nations Environment Programme. https://www.cbd.int/doc/c/c9de/d8ef/7225d7bb822f39ad3426c52b/cop-15-02-en.pdf

Ceccarelli, V., Ekué, M., Fremout, T., Gaisberger, H., Kettle, C., Taedoumg, H., Wouters, H. *et al.* 2022. Vulnerability mapping of 100 priority tree species in Central Africa to guide conservation and restoration efforts. *Biological Conservation*, 270: 109554. doi: 10.1016/j.biocon.2022.109554

Chakraborty, D., Móricz, N., Rasztovits, E., Dobor, L. & Schueler, S. 2021. Provisioning forest and conservation science with high-resolution maps of potential distribution of major European tree species under climate change. *Annals of Forest Science*, 78(2): 26. doi: 10.1007/s13595-021-01029-4

Chaloupková, K. & Lstibůrek, M. 2022. Spatial optimization of genetic thinning in seed orchards. *Ann For Sci*, 79: 37. doi: 10.1186/s13595-022-01158-4

Chandra, J. & Keshavkant, S. 2018. Desiccation-induced ROS accumulation and lipid catabolism in recalcitrant *Madhuca latifolia* seeds. *Physiol Mol Biol Plants*, 24: 75–87. doi: 10.1007/s12298-017-0487-y

Chang, S., Mahon, E.L., MacKay, H.A., Rottmann, W.H., Strauss, S.H., Pijut, P.M., Powell, W.A. *et al*. 2018. Genetic engineering of trees: progress and new horizons. *In Vitro Cellular Development Biology – Plant,* 54: 341–376. doi: 10.1007/s11627-018-9914-1

Chapman, D., Purse, B.V., Roy, H.E. & Bullock, J.M. 2017. Global trade networks determine the distribution of invasive non-native species. *Global Ecology and Biogeography*, 26(8): 907–917. doi: 10.1111/geb.12599

Charles-Dominique, T., Staver, A.C., Midgley, G.F. & Bond, W.J. 2015. Functional differentiation of biomes in an African savanna/forest mosaic. *South African Journal of Botany*, 101: 82-90. doi: 10.1016/j.sajb.2015.05.005

Chaudhary, R., Rönneburg, T., Stein Åslund, M., Lundén, K., Durling, M.B., Ihrmark, K., Menkis, A. *et al*. 2020. Marker-trait associations for tolerance to ash dieback in common ash (*Fraxinus excelsior* L.). *Forests*, 11(10): 1083. doi: 10.3390/f11101083

Cheddadi, R., Vendramin, G. G., Litt, T., François, L., Kageyama, M., Lorentz, S., Laurent, J.M. *et al.* 2006. Imprints of glacial refugia in the modern genetic diversity of *Pinus sylvestris*. *Global Ecology and Biogeography*, 15: 271–282. doi: 10.1111/j.1466-8238.2006.00226.x

Cheikh Albassatneh, M., Escudero, M., Monnet, A.C., Arroyo, J., Bacchetta, G., Bagnoli, F., Dimopoulos, P. *et al*. 2021. Spatial patterns of genus-level phylogenetic endemism in the tree flora of Mediterranean Europe. *Diversity and Distributions*, 27(5): 913–928. doi: 10.1111/ddi.13241

Chen, T.Y. & Lou, A.R. 2019. Phylogeography and paleodistribution models of a widespread birch (*Betula platyphylla* Suk.) across East Asia: Multiple refugia, multidirectional expansion, and heterogeneous genetic pattern. *Ecology and Evolution*, 9(13): 7792–7807. doi: 10.1002/ece3.5365

Chi, X., Guo, Q., Fang, J., Schmid, B. & Tang, Z. 2017. Seasonal characteristics and determinants of tree growth in a Chinese subtropical forest. *Journal of Plant Ecology*, 10: 4–12. doi: 10.1093/jpe/rtw051

Chiocchini, F., Mattioni, C., Pollegioni, P., Lusini, I., Martín, M.A., Cherubini, M., Lauteri, M. & Villani, F. 2016. Mapping the genetic diversity of *Castanea sativa*: exploiting spatial analysis for biogeography and conservation studies. *Journal of Geographic Information System*, 8(02): 248. doi: 10.4236/jgis.2016.82022

Chirwa, P.W., Akinnifesi, F.K., Sileshi, G., Syampungani, S., Kalaba, F.K. & Ajayi, O.C. 2008. Opportunity for conserving and utilizing agrobiodiversity through agroforestry in Southern Africa. *Biodiversity*, 9(1–2): 45–48. doi: 10.1080/14888386.2008.9712881

Christmas, M.J., Breed, M.F. & Lowe, A.J. 2016. Constraints to and conservation implications for climate change adaptation in plants. *Conservation Genetics*, 17(2): 305–320. doi: 10.1007/s10592-015-0782-5

Clark, L.G., X. Londoño, X. & Ruiz-Sanchez, E. 2015. Bamboo taxonomy and habitat. In: W. Liese & M. Koehl, eds. *Bamboo, the plant and its uses*, pp. 1–30. Heidelberg, Germany, Springer Verlag, Tropical Forestry Series.

Coates, D.J., McArthur, S.L. & Byrne, M. 2015. Significant genetic diversity loss following pathogen driven population extinction in the rare endemic *Banksia brownii*. *Biological Conservation*, 192: 353–360. doi: 10.1016/j.biocon.2015.10.013

Coates, D.J., Byrne, M. & Moritz, C. 2018. Genetic diversity and conservation units: dealing with the species-population continuum in the age of genomics. *Frontiers in Ecology and Evolution*, 6: 165. doi: 10.3389/fevo.2018.00165

Conedera, M., Krebs, P., Tinner, W., Pradella, M. & Torriani, D. 2004. The cultivation of *Castanea sativa* (Mill.) in Europe, from its origin to its diffusion on a continental scale. *Vegetation History and Archaeobotany*, 13: 161–179. doi: 10.1007/s00334-004-0038-7

Conradi, T., Slingsby, J.A., Midgley, G.F., Nottebrock, H., Schweiger, A.H. & Higgins, S.I. 2020. An operational definition of the biome for global change research. *New Phytologist*, 227(5): 1294–1306. doi: 10.1111/nph.16580

Conroy, G.C., Shimizu-Kimura, Y., Lamont, - R.W. & Ogbourne, S.M. 2019. A multidisciplinary approach to inform assisted migration of the restricted rainforest tree, *Fontainea rostrata*. *PLoS ONE*, 14(1): e0210560. doi: 10.1371/journal.pone.0210560

Cornelius, J.P., Bayala, J., Trent, B., Catacutan, D., Degrande, A., Kindt, R., Leimona, B. *et al.* 2019. Agroforestry. In: *The State of the World's Biodiversity for Food and Agriculture*, pp. 233–241. J. Bélanger & D. Pilling, eds. FAO Commission on Genetic Resources for Food and Agriculture Assessments. Rome, FAO. doi: 10.4060/CA3129EN

Correia, M., Diabaté, M., Beavogui, P., Guilavogui, K., Lamanda, N. & de Foresta, H. 2010. Conserving forest tree diversity in Guinée forestière (Guinea, West Africa): the role of coffee-based agroforests. *Biodiversity and Conservation*, 19: 1725–1747. doi: 10.1007/s10531-010-9800-6

Couvreur, T.L.P., Forest, F. & Baker, W.J. 2011. Origin and global diversification patterns of tropical rain forests: inferences from a complete genus-level phylogeny of palms. *BMC Biology*, 9: 44. doi: 10.1186/1741-7007-9-44

Crandall, K.A., Bininda-Emonds, O.R., Mace, G.M. & Wayne, R.K. 2000. Considering evolutionary processes in conservation biology. *Trends in Ecology & Evolution*, 15(7): 290–295. doi: 10.1016/S0169-5347(00)01876-0

Cronn, R.C., Finch, K.N., Hauck, L.L., Parker-Forney, M., Milligan, B.G., Dowling, J. & Adventure scientists. 2021. Range-wide assessment of a SNP panel for individualization and geolocalization of bigleaf maple (*Acer macrophyllum* Pursh). *Forensic Science International: Animals and Environments*, 1: 100033. doi: 10.1016/j.

fsiae.2021.100033

Cubry, P., Gallagher, E., O'Connor, E. & Kelleher, C.T. 2015. Phylogeography and population genetics of black alder (*Alnus glutinosa* (L.) Gaertn.) in Ireland: putting it in a European context. *Tree Genetics & Genomes*, 11(5): 99. doi: 10.1007/s11295-015-0924-4

Cusack, V. 1999. *Bamboo world, the growing and use of clumping bamboos*. Sydney, Australia, Kangaroo Press.

Daïnou, K., Flot, J.F., Degen, B., Blanc-Jolivet, C., Doucet, J.L., Lassois, L. & Hardy O.J. 2017. DNA taxonomy in the timber genus Milicia: evidence of unidirectional introgression in the West African contact zone. *Tree Genetics & Genomes*, 13(4): 1-12. doi: 10.1007/s11295-017-1174-4

Danthu, P., Michel, I., Carrière, S. M., Labeyrie, V., Rakouth, B., Sarron, J., Mariel, J. *et al*. 2022. Coming from elsewhere: the preponderance of introduced plant species in agroforestry systems on the east coast of Madagascar. *Agroforestry Systems*, 96: 697–716. doi: 10.1007/s10457-022-00732-z

Das, T. & Das, A.K. 2005. Inventorying plant biodiversity in homegardens: a case study in Barak Valley, Assam, North East India. *Current Science*, 89: 155–163. https://www.jstor.org/stable/24110441

Dauby, G., Duminil, J., Heuertz, M., Koffi, G.K., Stevart, T. & Hardy, O.J. 2014. Congruent phylogeographical patterns of eight tree species in Atlantic Central Africa provide insights into the past dynamics of forest cover. *Molecular ecology*, 23(9): 2299-2312. doi: 10.1111/mec.12724

David, A., Keith, JR., FP., Nicholson, E., Kingsford, RT. 2020. IUCN Global Ecosystem Typology. 2.0 Descriptive profiles for biomes and ecosystem functional groups.

Davies, R.M., Hudson, A.R., Dickie, J.B. *et al.* 2020. Exploring seed longevity of UK native trees: implications for ex situ conservation. *Seed Sci Res*, 30: 101–111. doi: 10.1017/s0960258520000215

Davis, K.T., Dobrowski, S.Z., Higuera, P.E., Holden, Z.A., Veblen, T.T., Rother, M.T., Parks, S.A. *et al.* 2019. Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences*, 116(13): 6193–6198. doi: 10.1073/pnas.18151071

Daws, M.I., Garwood, N.C. & Pritchard, H.W. 2006. Prediction of desiccation sensitivity in seeds of woody species: a probabilistic model based on two seed traits and 104 species. *Ann Bot*, 97: 667. doi: 10.1093/aob/mcl022

Dawson, I. K., Guariguata, M. R., Loo, J., Weber, J. C., Lengkeek, A., Bush, D., Cornelius, J. *et al*. 2013. What is the relevance of smallholders' agroforestry systems for conserving tropical tree species and genetic diversity in *circa situm*, *in situ* and *ex situ* settings? A review. *Biodiversity and Conservation*, 22: 301–324. doi: 10.1007/s10531-012-0429-5

Dawson, I. K., van Breugel, P., Coe, R., Kindt, R., van Zonneveld, M., Lillesø, J-PB., Graudal, L. *et al*. 2017. A meta-analysis of molecular marker genetic datasets for eastern Africa trees supports the utility of potential natural vegetation maps for planning climate-smart restoration initiatives. *Tree Genetics & Genomes*, 13: 71. doi: 10.1007/s11295-017-1155-7

Dawson, I.K., Park, S.E., Attwood, S.J., Jamnadass, R., Powell, W., Sunderland, T. & Carsan S. 2019. Contributions of biodiversity to the sustainable intensification of food production. *Global Food Security*, 21: 23-37. doi: 10.1016/j.gfs.2019.07.002

Dawson, I.K., Karanja, A., Kindt, R., Thomson, L., Ngethe, E., McMullin, S., Lillesø, J.-P.B. *et al.* 2025. Data on the area extent of other wooded land and of agroforestry systems globally, as extracted from major studies and as summarised by geographic region. doi: 10.5281/ZENODO.14700675

de Foresta, H. 2017. Where are the trees outside forest in Brazil? *Pesquisa Florestal Brasileira*, 37: 393–401. doi: 10.4336/2017.pfb.37.91.1390

de Miguel, M., Rodríguez-Quilón, I., Heuertz, M., Hurel, A., Grivet, D., Jaramillo-Correa, J.P., Vendramin, G.G. *et al*. 2022. Polygenic adaptation and negative selection across traits, years and environments in a long-lived plant species (*Pinus pinaster* Ait., Pinaceae). *Molecular Ecology*, 31(7): 2089–2105. doi: 10.1111/mec.16367

de Vitis, M., Hay, F.R., Dickie, J.B. *et al.* 2020. Seed storage: maintaining seed viability and vigor for restoration use. *Restor Ecol*, 28: S249–S255. doi: 10.1111/rec.13174

de Vries, S.M.G., Alan, M., Bozzano, M., Burianek, V., Collin, E., Cottrell, J., Ivankovic, M. *et al*. 2015. Pan-European strategy for genetic conservation of forest trees and establishment of a core network of dynamic conservation units. European Forest Genetic Resources Programme (EUFORGEN). Rome, Bioversity International.

Degen, B. & Sebbenn, A. M. 2021. Genetics and Tropical Forests. In: Köhl, M. & Pancel, L. (eds.) *Tropical Forestry Handbook*. Berlin, Heidelberg: Springer Berlin Heidelberg.

Delzon, S., Urli, M., Samalens, J.C., Lamy, J.B., Lischke, H., Sin, F., Zimmermann, N.E. *et al*. 2013. Field evidence of colonisation by holm oak, at the northern margin of its distribution range, during the Anthropocene period. *PLoS ONE*, 8(11): 1–11. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0080443

Demenou, B.B., Piñeiro, R. & Hardy, O.J. 2016. Origin and history of the Dahomey Gap separating West and Central African rain forests: insights from the phylogeography of the legume tree *Distemonanthus benthamianus*. *Journal of Biogeography,* 43(5): 1020–1031. doi: 10.1111/jbi.12688

Depardieu, C., Gérardi, S., Nadeau, S., Parent, G.J., Mackay, J., Lenz, P., Lamothe, M. *et al.* 2021. Connecting tree-ring phenotypes, genetic associations and transcriptomics to decipher the genomic architecture of drought adaptation in a widespread conifer. *Molecular Ecology*, 30(16): 3898–3917. doi: 10.1111/mec.15846

DeWoody, J.A., Harder, A.M., Mathur, S. & Willoughby, J.R. 2021. The long-standing significance of genetic diversity in conservation. *Molecular Ecology*, 30(17): 4147–4154. doi: 10.1111/mec.16051

Diazgranados, M., Allkin, B., Black, N., Cámara-Leret, R., Canteiro, C., Carretero, J., Eastwood, R. *et al.* 2020. *World checklist of useful plant species*. Kew, UK, Royal Botanic Gardens. https://kew.iro.bl.uk/downloads/a595f76e-3dcc-48a5-94f4-1ab339ea11ec?locale=en

Dick, C.W., Hardy, O.J., Jones, F.A. & Petit, R.J. 2008. Spatial scales of pollen and seed-mediated gene flow in tropical rain forest trees. *Tropical Plant Biology,* 1: 20–33. https://doi.org/10.1007/s12042-007-9006-6

Dickie, J.B. & Bowyer, J.T. 1985. Estimation of provisional seed viability constants for apple (*Malus domestica* Borkh. cv. Greensleeves). *Ann Bot*, 56: 271–275. doi: 10.1093/oxfordjournals.aob.a087012

Dickie, J.B., Ellisf, R.H., Kraakj, H.L. *et al.* 1990. Temperature and seed storage longevity. *Ann Bot*, 65: 197–204. doi: 10.1093/oxfordjournals.aob.a087924

Diniz-Filho, J.A.F., de Oliveira Ferraz Barbosa, A.C., Chaves, L.J., da Silva e Souza, K., Dobrovolski, R., Rattis, L., Terribile, L.C. *et al*. 2020. Overcoming the worst of both worlds: integrating climate change and habitat loss into spatial conservation planning of genetic diversity in the Brazilian Cerrado. *Biodiversity and Conservation*, 29(5): 1555–1570. doi: 10.1007/s10531-018-1667-y

Dixon, P.G. & Gibson, L.J. 2014. The structure and mechanics of Moso bamboo material. *Journal of the Royal Society Interface*, 11: 20140321. doi: 10.1098/rsif.2014.0321

Dobhal, S., Sharma, S., Ahmed, N. & Kumar, A. 2019. Genetic polymorphism in *Dalbergia sissoo* Roxb. using RAPD markers. *Indian Journal of Biotechnology*, 18: 164–173.

Domínguez, J., Macaya-Sanz, D., Gil, L., & Martín, J.A. 2022. Excelling the progenitors: Breeding for resistance to Dutch elm disease from moderately resistant and susceptible native stock. *Forest Ecology and Management*, 511, 120113. doi: 10.1016/j.foreco.2022.120113

Dompreh, D., Swaine, M.D. & Wilcock, C.C. 2015. Reproductive biology of the critically endangered tropical tree *Talbotiella gentii*. *Southern Forests: a Journal of Forest Science*, 77(2): 153–163. doi:

10.2989/20702620.2014.1001674

Dransfield, J., Uhl, N.W., Asmussen, C.B., Baker, W. J., Harley, M.M. & Lewis, C.E. 2008. *Genera Palmarum - the evolution and classification of palms*. Royal Botanic Gardens, Kew, Richmond.

Dransfield, S. & Widjaja, E., eds. 1995. *Bamboos*. Vol. 7, Plant resources of South-East Asia (PROSEA). Leiden, Netherlands, Backhuys Publishers.

Druckenbrod, D.L., Martin‐Benito, D., Orwig, D.A., Pederson, N. Poulter, B., Renwick, K.M. & Shugart, H.H. 2019. Redefining temperate forest responses to climate and disturbance in the eastern United States: New insights at the mesoscale. *Global Ecology and Biogeography*, 28: 557–575. doi: 10.1111/geb.12876

Du, Q., Gong, C., Wang, Q., Zhou, D., Yang, H., Pan, W., Li, B. *et al.* 2016. Genetic architecture of growth traits in *Populus* revealed by integrated quantitative trait locus (QTL) analysis and association studies. *New Phytologist*, 209: 1067–1082. doi: 10.1111/nph.13695

Dudley, N. & Phillips, A. 2006. *Forests and protected areas: Guidance on the use of the IUCN protected area management categories*. Gland, Switzerland and Cambridge, UK, IUCN. x + 58pp. https://portals.iucn.org/library/node/8804

Dudley, N. ed. 2008. *Guidelines for applying protected area management categories*. Gland, Switzerland, IUCN. https://portals.iucn.org/library/sites/library/files/documents/pag-021.pdf

Duminil, J., Mona, S., Mardulyn, P., Doumenge, C., Walmacq, F., Doucet, J.-L., & Hardy, O.J. 2015. Late Pleistocene molecular dating of past population fragmentation and demographic changes in African rain forest tree species supports the forest refuge hypothesis. *Journal of Biogeography*, 42: 1443–1454. doi: 10.1111/jbi.12510

Duminil, J., Daïnou, K., Kaviriri, D.K., Gillet, P., Loo, J., Doucet, J.L. & Hardy O.J. 2016. Relationships between population density, fine-scale genetic structure, mating system and pollen dispersal in a timber tree from African rainforests. *Heredity*, 116(3): 295–303. DOIdoi: 10.1038/hdy.2915,191

Dumroese, R.K., Williams, M.I., Stanturf, J.A. & Clair, J. 2015. Considerations for restoring temperate forests of tomorrow: forest restoration, assisted migration, and bioengineering. *New Forests*, 46(5): 947–964. doi: 10.1007/s11056-015-9504-6

Dun, H. F., Hung, T. H., Green, S., & MacKay, J. J. 2022. Comparative transcriptomic responses of European and Japanese larches to infection by *Phytophthora ramorum*. *BMC Plant Biology*, *22*(1): 480. doi: 10.1186/s12870-022-03806-3

Durai, J. & Trinh, T.L. 2019. *Manual for Sustainable Management of Clumping Bamboo Forest*. INBAR Technical Report No. 4. Beijing, International Bamboo and Rattan Organisation.

Durrant, TH., Rigo, DD. & Caudullo, G. 2016. *Pinus sylvestris*. *European Atlas of Forest Tree Species*, 132–133.

Eckert, A.J., Wegrzyn, J.L., Liechty, J.D., Lee, J.M., Cumbie, W.P., Davis, J.M. *et al*. 2013. The evolutionary genetics of the genes underlying phenotypic associations for loblolly pine *(Pinus taeda*, Pinaceae). *Genetics*, 195(4):1353–1372. doi: 10.1534/genetics.113.157198

Eckert, C.G., Kalisz, S., Geber, M.A., Sargent, R., Elle, E., Cheptou, P.O. *et al.* 2010. Plant mating systems in a changing world. *Trends in Ecology & Evolution*, 25(1): 35–43.

Edwards, C.E. 2015. Looking to the future of conservation genetics: The case for using quantitative genetic experiments to estimate the ability of rare plants to withstand climate change. *American Journal of Botany,* 102: 1011–1013. doi: 10.3732/ajb.1500145

Eizaguirre, C. & Baltazar‐Soares, M. 2014. Evolutionary conservation—evaluating the adaptive potential of species. *Evolutionary Applications*, 7(9): 963–967. doi: 10.1111/eva.12227

Elias, M. 2015. Gender, knowledge-sharing and management of shea (*Vitellaria paradoxa*) parklands in central-west Burkina Faso. *Journal of Rural Studies*, 38: 27–38. doi: 10.1016/J.JRURSTUD.2015.01.006

Elias, M., Jalonen, R., Fernandez, M. & Grosse,

A. 2017. Gender-responsive participatory research for social learning and sustainable forest management. *Forests, Trees and Livelihoods*, 26(1): 1–12. doi: 10.1080/14728028.2016.1247753

El-Kassaby, Y.A. & Lstibůrek, M. 2009. Breeding without breeding. *Genetics Research*, 91(2): 111–120. doi: 10.1017/S001667230900007X

Ellegren, H. & Galtier, N. 2016. Determinants of genetic diversity. *Nature Reviews Genetics*, 17(7): 422–433. doi: 10.1038/nrg.2016.58

Ellis, R.H. & Roberts, E.H. 1980. Improved equations for the prediction of seed longevity. *Ann Bot*, 45: 13–30. doi: 10.1093/oxfordjournals.aob.a085797

Ellis, R.H., Mai-Hong, T., Hong, T.D. *et al.* 2007. Comparative analysis by protocol and key of seed storage behaviour of sixty Vietnamese tree species. *Seed Sci Technol*, 35: 460–476. doi: 10.15258/sst.2007.35.2.20

Ellis, R.H. 2022. Seed ageing, survival and the improved seed viability equation; forty years on. *Seed Sci Technol*, 50: 1–20. doi: 10.15258/sst.2022.50.1.s.01

Ellstrand, N.C. 2014. Is gene flow the most important evolutionary force in plants? *American Journal of Botany*, 101(5): 737–753. doi: 10.3732/ajb.1400024

Emerald Ash Borer Network. Undated. [Cited 14 November 2024]. https://www.emeraldashborer.info/

Enderle, R., Stenlid, J. & Vasaitis, R. 2019. An overview of ash (*Fraxinus* spp.) and the ash dieback disease in Europe. *CAB Reviews*, 14: 1–12. doi: 10.1079/PAVSNNR201914

Engelmann, F. 2012. Germplasm collection, storage, and conservation. In: *Plant Biotechnol Agric*, pp. 255–267. doi: 10.1016/b978-0-12-381466-1.00017-1

Engels, J. & Rudebjer, P. 2017. Strengthening institutions and organizations, and building capacity for the conservation and use of agricultural biodiversity. In: D. Hunter, L. Guarino, C. Spillane & P.C. McKeown, eds. *Routledge handbook of agricultural biodiversity,* pp. 627–646. London, Routledge. https://cgspace.cgiar.org/handle/10568/90409

Enquist, B.J., Feng, X., Boyle, B., Maitner, B., Newman, E.A., Møller Jørgensen, P., Roehrdanz, P.R. *et al*. 2019. The commonness of rarity: Global and future distribution of rarity across land plants. *Science Advances,* 5(11). doi: 10.1126/sciadv.aaz0414

Esseen, P.-A., Ehnström, B., Ericson, L. & Sjöberg, K. 1997. Boreal Forests. *Ecological Bulletins*, 16–47.

EUFORGEN (European Forest Genetic Resources Programme). 2021. *Forest Genetic Resources Strategy For Europe*. European Forest Institute.

https://www.euforgen.org/fileadmin/templates/euforgen.org/upload/Publications/Thematic_publications/FGR_Strategy4Europe.pdf

EUFORGEN. 2023. *Overview - EUFORGEN European FGR Programme*. [Cited 23 September 2023]. https://www.euforgen.org/about-us/overview/

EVOLTREE. 2024. *Mission & purpose*. [Cited 23 January 2024]. https://www.evoltree.eu/about/mission-purpose

Ewédjè, E.E.B., Ahanchédé, A., Hardy, O.J. & Ley, A.C. 2015. Reproductive biology of *Pentadesma butyracea* (Clusiaceae), source of a valuable non timber forest product in Benin. *Plant Ecology and Evolution*, 148(2): 213–228. doi: 10.5091/plecevo.2015.998

Ewédjè, E.E.B.K., Jansen, S., Koffi, G.K., Staquet, A., Piñeiro, R., Essaba, R.A., Laurier, N. *et al*. 2020. Species delimitation in the African tree genus *Lophira* (Ochnaceae) reveals cryptic genetic variation. *Conservation Genetics*, 21(3): 501–514. doi: 10.1007/s10592-020-01265-7

Exposito-Alonso, M., Booker, T.R., Czech, L., Gillespie, L., Hateley, S., Kyriazis, C.C., *et al*. 2022. Genetic diversity loss in the Anthropocene. *Science*, 377: 1431–1435. doi: 10.1126/science.abn5642

Fady, B., Aravanopoulos, F.A., Alizoti, P., Mátyás, C., von Wühlisch, G., Westergren, M. *et al*. 2016. Evolution-based approach needed for the conservation and silviculture of peripheral forest tree populations. *Forest Ecology and Management*, 375: 66–75. doi: 10.1016/j.foreco.2016.05.015

Fady, B., Aravanopoulos, F., Benavides, R., González-Martínez, S., Grivet, D., Lascoux, M., Lindner, M. *et al.* 2020. Genetics to the rescue: managing forests sustainably in a changing world. *Tree Genetics & Genomes*, 16(6): 80. doi: 10.1007/s11295-020-01474-8

Fady, B., & Bozzano, M. 2021. Effective population size does not make a practical indicator of genetic diversity in forest trees. *Biological Conservation*, 253, 108904. doi: 10.1016/J.BIOCON.2020.108904

Falk, T., Herndon, N., Grau, E., Buehler, S., Richter, P., Zaman, S., Baker, E.M, *et al.* 2018. Growing and cultivating the forest genomics database, TreeGenes. *Database*, Jan 1:2018: 1–11. doi: 10.1093/database/bay084

Fan, D., Liu, T., Li, C., Jiao, B., Li, S., Hou, Y. *et al*. 2015. Efficient CRISPR/Cas9-mediated targeted mutagenesis in Populus in the first generation. *Scientific Reports,* 5: 12217. doi: 10.1038/srep12217

Fantinatti, J.B. & Usberti, R. 2007. Seed viability constants for *Eucalyptus grandis*. *Pesq Agropec Bras*: 111–117. doi: 10.1590/s0100-204x2007000100015

FAO & AOAD (Arab Organization for Agricultural Development). 2021. *Regional Assessment of Forest Education in Near East and North Africa*. Rome, FAO. https://www.fao.org/3/cb6740en/cb6740en.pdf

FAO & FILAC. 2021. *Los pueblos indígenas y tribales y la gobernanza de los bosques. Una oportunidad para la acción climática en América Latina y el Caribe*. Santiago. doi:10.4060/cb2953es

FAO & UNEP. 2020. *The State of the World's Forests 2020. Forests, Biodiversity and People.* Rome, FAO. doi:10.4060/ca8642en

FAO, DFSC & IPGRI. 2001. *Forest genetic resources conservation and management. In managed natural forests and protected areas (*in situ*).* Vol. 2. Rome, International Plant Genetic Resources Institute. https://hdl.handle.net/10568/105323

FAO. 2006. Report of the Expert Consultation on Global Forest Resources Assessment (FRA): Towards FRA 2010. Rome. https://www.fao.org/3/a-bc249e.pdf

FAO. 2009a. *International Treaty on Plant Genetic Resources for Food and Agriculture*. Rome. https://www.fao.org/3/i0510e/i0510e.pdf

FAO. 2009b. *Global review of forest pests and diseases*. FAO Forestry Paper 156. Rome. https://www.fao.org/3/i0640e/i0640e.pdf

FAO. 2010a. Global ecological zones for FAO forest reporting: 2010 update. *Forest Resources Assessment Working Paper 179.*

FAO. 2010b. *Forests and genetically modified trees.* Rome. https://www.fao.org/3/i1699e/i1699e.pdf

FAO. 2010c. *Developing effective forest policy: A guide.* FAO Forestry Paper No. 161. Rome. https://www.fao.org/3/i1679e/i1679e.pdf

FAO. 2011. *Biotechnologies for agricultural development.* Proceedings of the FAO International Technical Conference on Agricultural Biotechnologies in Developing Countries: Options and Opportunities in Crops, Forestry, Livestock, Fisheries and Agro-industry to Face the Challenges of Food Insecurity and Climate Change (ABDC-10). Rome. https://openknowledge.fao.org/handle/20.500.14283/i5922e

FAO. 2014a. *The State of the World's Forest Genetic Resources*. Rome. https://openknowledge.fao.org/handle/20.500.14283/i3825e

FAO. 2014b. *Global plan of action for the conservation, sustainable use and development of forest genetic resources*. FAO Commission on Genetic Resources for Food and Agriculture. Rome. https://openknowledge.fao.org/handle/20.500.14283/i3849e

FAO. 2015. *Voluntary guidelines to support the integration of genetic diversity into national climate change adaptation planning*. FAO Commission on Genetic Resources for Food and Agriculture. Rome. www.fao.org/3/a-i4940e.pdf

FAO. 2017. *Addressing agriculture, forestry and fisheries in national adaptation plans. Supplementary guidelines*. Rome. www.fao.org/3/a-i6714e.pdf

FAO. 2018a. *The State of the World's Forests 2018 -*

Forest pathways to sustainable development. Rome. https://www.fao.org/documents/card/en/c/I9535EN

FAO. 2018b. Terms and definitions. FRA 2020. *Forest Resources Assessment Working Paper No. 188*. https://www.fao.org/3/I8661EN/i8661en.pdf

FAO. 2018c. *Exploratory fact-finding scoping study on "digital sequence information" on genetic resources for food and agriculture*. Commission on Genetic Resources for Food and Agriculture. Background Study Paper No. 68. Rome. https://openknowledge.fao.org/server/api/core/bitstreams/178e26e0-b1f2-416d-9521-eabd92b352d0/content

FAO. 2018d. *Report of the Twenty-seventh Session of the Asia-Pacific Forestry Commission, Colombo, Sri Lanka, 24-27 October 2017*. Bangkok, FAO Regional Office for Asia and the Pacific. https://openknowledge.fao.org/items/c0d626b0-9fcd-42d0-b999-ac2ba7779fb5

FAO & Commission on Genetic Resources for Food and Agriculture. 2019a. Report of the Commission on Genetic Resources for Food and Agriculture Seventeenth Regular Session. Rome, 18–22 February 2019. Rome. https://www.fao.org/3/mz618en/mz618en.pdf

FAO & Commission on Genetic Resources for Food and Agriculture. 2019b. First Report on the Implementation of the Global Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources. Seventeenth Regular Session of the Commission on Genetic Resources for Food and Agriculture. Rome, 18–22 February 2019. CGRFA-17/19/10.2/Inf.1. Rome. https://www.fao.org/3/my877en/my877en.pdf

FAO. 2019a. *The State of the World's Biodiversity for Food and Agriculture*, J. Belanger & D. Pilling (eds.). FAO Commission on Genetic Resources for Food and Agriculture Assessments. Rome. http://www.fao.org/3/CA3129EN/CA3129EN.pdf.

FAO. 2019b. *Trees, forests and land use in drylands: the first global assessment*. Full Report. FAO Forestry Paper No. 184. Rome.

FAO. 2020a. *Global Forest Resources Assessment 2020: Main report*. Rome. doi:10.4060/ca9825en

FAO. 2020b. *FAO Strategy on Mainstreaming Biodiversity across Agricultural Sectors*. Rome. doi:10.4060/ca7722en

FAO. 2021. *2021-23 Action Plan for the Implementation of the FAO Strategy on Mainstreaming Biodiversity across Agricultural Sectors*. Rome. doi:10.4060/cb5515en

FAO. 2022a. *The State of the World's Forests 2022. Forest pathways for green recovery and building inclusive, resilient and sustainable economies*. Rome. https://www.fao.org/documents/card/en/c/cb9360en

FAO. 2022b. *FAO Yearbook of Forest Products 2020*. Rome. doi:10.4060/cc3475m

FAO. 2022c. *FRA 2020 Remote Sensing Survey*. FAO Forestry Paper No. 186. Rome. https://doi.org/10.4060/cb9970en

FAO. 2022d. *Gene editing and agrifood systems*. Rome. doi: 10.4060/cc3579en

FAO. 2022e. *World Food and Agriculture – Statistical Yearbook 2022*. Rome. doi:10.4060/cc2211en

FAO. 2022. *FAO Strategy on Climate Change 2022–2031*. Rome. https://openknowledge.fao.org/handle/20.500.14283/cc2274en

FAO. 2023a. *The world's mangroves 2000–2020*. Rome. doi:10.4060/cc7044en

FAO. 2023b. *Terms and definitions. FRA 2025*. Forest Resources Assessment Working Paper No. 194. Rome.

FAO. 2025. *Voluntary guidelines for preparing a national strategy for forest genetic resources*. Rome. [forthcoming]

Farrant, J.M., Pammenter, N.W. & Berjak, P. 1992. Development of the recalcitrant (homoiohydrous) seeds of *Avicennia marina*: anatomical, ultrastructural and biochemical events associated with development from histodifferentiation to maturation. *Ann Bot*, 70: 75–86. doi: 10.1093/oxfordjournals.aob.a088442

Farrant, J.M., Pammenter, N.W., Berjak, P. & Walters, C. 1997. Subcellular organization and metabolic activity during the development of seeds that attain different levels of desiccation tolerance. *Seed Sci Res*, 7: 135–144. doi: 10.1017/

s0960258500003470

Farrelly, D. 1984. *The book of bamboo: a comprehensive guide to this remarkable plants, its uses, and its history*. San Francisco, USA, Sierra Club Books.

Fernandez-Fournier, P., Lewthwaite, J.M. & Mooers, A.Ø. 2021. Do we need to identify adaptive genetic variation when prioritizing populations for conservation? *Conservation Genetics*, 22(2): 205–216. doi: 10.1007/s10592-020-01327-w

Fernandez-Vega, J., Covey, K.R. & Ashton, M.S. 2017. Tamm Review: Large-scale infrequent disturbances and their role in regenerating shade-intolerant tree species in Mesoamerican rainforests: Implications for sustainable forest management. *Forest Ecology and Management*, 395: 48–68. doi: 10.1016/j.foreco.2017.03.025

Ferrenberg, S. 2016. Landscape features and processes influencing forest pest dynamics. *Current Landscape Ecology Reports*, 1(1): 19–29. doi: 10.1007/s40823-016-0005-x

Fikret, I. & McKeand, S.E. 2019. Fourth cycle breeding and testing strategy for *Pinus taeda* in the NC State University Cooperative Tree Improvement Program. *Tree Genetics & Genomes*, 15: 70. doi: 10.1007/s11295-019-1377-y

Fine, P.V.A. & Ree, R.H. 2006. Evidence for a time-integrated species-area effect on the latitudinal gradient in tree diversity. *The American Naturalist*, 168(6): 796–804. doi:10.1086/508635

FitzJohn, R.G., Pennell, M.W., Zanne, A.E., Stevens, P.F., Tank, D.C. & Cornwell, W.K. 2014. How much of the world is woody? *Journal of Ecology*, 102(5): 1266–1272. doi: 10.1111/1365-2745.12260

Flanagan, S.P., Forester, B.R., Latch, E.K., Aitken, S.N. & Hoban, S. 2018. Guidelines for planning genomic assessment and monitoring of locally adaptive variation to inform species conservation. *Evolutionary Applications*, 11(7): 1035–1052. doi: 10.1111/eva.12569

Foden, W.B., Butchart, S.H.M., Stuart, S.N., Vié, J.-C., Akçakaya, H.R., Angulo, A. *et al.* 2013. Identifying the world's most climate change vulnerable species: A systematic trait-based assessment of all birds, amphibians and corals. *PLoS ONE*, 8(6): e65427. doi: 10.1371/journal.pone.0065427

FOEN (Federal Office for the Environment), ed. 2022. *Alien species in Switzerland. An inventory of alien species and their impact. Situation as of 2022*. Environmental Studies No 2220. Bern.

FOREST EUROPE. 2020. State of Europe's Forests 2020. FOREST EUROPE Liaison Unit. Bratislava, Slovakia. https://foresteurope.org/wp-content/uploads/2016/08/SoEF_2020.pdf

Franić, I., Allan, E., Prospero, S., Adamson, K., Attorre, F., Auger-Rozenberg, M.-A., Augustin, S. *et al*. 2023. Climate, host and geography shape insect and fungal communities of trees. *Scientific Reports*, 13: 11570. doi: 10.1038/s41598-023-36795-w

Frankel, O.H., Brown, A.H. & Burdon, J.J. eds. 1995. *The conservation of plant biodiversity*. New York, USA, Cambridge University Press.

Frankham, R., Bradshaw, C.J. & Brook, B.W. 2014. Genetics in conservation management: revised recommendations for the 50/500 rules, Red List criteria and population viability analyses. *Biological Conservation*, 170: 56–63. doi: 10.1016/j.biocon.2013.12.036

Franklin, I.R. 1980. Evolutionary change in small populations. In: M.E. Soulé & B.A. Wilcox, eds. *Conservation biology: an evolutionary-ecological perspective*, pp. 135–150. Sunderland, USA, Sinauer.

Fremout, T., Thomas, E., Gaisberger, H., Van Meerbeek, K., Muenchow, J., Briers, S., Gutierrez-Miranda, C.E. *et al*. 2020. Mapping tree species vulnerability to multiple threats as a guide to restoration and conservation of tropical dry forests. *Global Change Biology*, 26(6): 3552–3568. doi: 10.1111/gcb.15028

Fremout, T., Gutiérrez-Miranda, C.E., Briers, S., Marcelo-Peña, J.L., Cueva-Ortiz, E., Linares-Palomino, R., La Torree-Cuadros *et al*. 2021. The value of local ecological knowledge to guide tree species selection in tropical dry forest restoration. *Restoration Ecology*, 29(4): e13347. doi: 10.1111/rec.13347

Fu, R., Zhu, Y., Liu, Y., Feng, Y., Lu, R. S., Li, Y., Li, P. *et al*. 2022. Genome-wide analyses of introgression between two sympatric Asian oak species. *Nature Ecology & Evolution*, 6(7): 924–935. doi: .1038/s41559-022-01754-7

Fugeray-Scarbel, A., Bouffier, L., Lemarié, S., Sánchez, L., Alia, R., Biselli, C., Buiteveld, J. *et al.* 2024. Prospects for evolution in European tree breeding. *iForest*, 17: 45–58. doi: 10.3832/ifor4544-017

Funda, T. & El-Kassaby, Y.A. 2012. Seed orchard genetics. *CAB Rev*, 7: 13. doi: 10.1079/pavsnnr20127013

Funk, W.C., McKay, J.K., Hohenlohe, P.A. & Allendorf, F.W. 2012. Harnessing genomics for delineating conservation units. *Trends in Ecology & Evolution*, 27(9): 489–496. doi: 10.1016/j.tree.2012.05.012

Fussi, B., Westergren, M., Aravanopoulos, F., Baier, R., Kavaliauskas, D., Finzgar, D. *et al.* 2016. Forest genetic monitoring: an overview of concepts and definitions. *Environmental Monitoring and Assessment*, 188: 493. doi: 10.1007/s10661-016-5489-7

Gachuiri, A., Paez-Valencia, A.M., Elias, M., Carsan, S. & McMullin, S. 2022. Gender and generational differences in local knowledge and preference for food trees in Central Uganda and Eastern Kenya. *Frontiers in Sustainable Food Systems*, 5: 746256. doi: 10.3389/fsufs.2021.746256

Gailing, O., Bodénès, C., Finkeldey, R., Kremer, A. & Plomion, C. 2013. Genetic mapping of EST-derived simple sequence repeats (EST-SSRs) to identify QTL for leaf morphological characters in a *Quercus robur* full-sib family. *Tree Genetics & Genomes*, 9: 1361–1367. doi: 10.1007/s11295-013-0633-9

Gailing, O. & Nelson, C.D. 2017. Genetic variation patterns of American chestnut populations at EST-SSRs. *Botany*, 95: 799–807. doi: 10.1139/cjb-2016-0323

Gaisberger, H., Kindt, R., Loo, J., Schmidt, M., Bognounou, F., Da, S.S., Diallo, O.B. *et al*. 2017. Spatially explicit multi-threat assessment of food tree species in Burkina Faso: A fine-scale approach. *PLoS ONE*, 12(9): e0184457. doi: 10.1371.journal.pone.0183357

Gaisberger, H., Legay, S., Andre, C., Loo, J., Azimov, R., Aaliev, S., Bobokalonov, F. *et al.* 2020. Diversity under threat: connecting genetic diversity and threat mapping to set conservation priorities for *Juglans regia* L. populations in Central Asia. *Frontiers in Ecology and Evolution*, 8: 171. doi: 10.3389/fevo.2020.00171

Gaisberger, H., Fremout, T., Kettle, C.J., Vinceti, B., Kemalasari, D., Kanchanarak, T., Thomas, E. *et al*. 2022a. Tropical and subtropical Asia's valued tree species under threat. *Conservation Biology*, 36(3): e13873. doi: 10.1111/cobi.13873

Gaisberger, H., Fremout, T., So, T., Thammavong, B., Bounithiphonh, C., Hoa, T.T., Yongqi, Z. *et al*. 2022b. Range-wide priority setting for the conservation and restoration of Asian rosewood species accounting for multiple threats and ecogeographic diversity. *Biological Conservation*, 270:109560. doi: 10.1016/j.biocon.2022.109560

Gaisberger, H., Jalonen, R., Vinceti, B., Elias, M., Kettle, C.J., Thomas, E., DeRidder, B. *et al.* 2023. *Delivering tree genetic resources in forest and landscape restoration – A guide to ensuring local and global impact*. Forestry Working Paper, No. 40. Rome, FAO. doi: 10.4060/cc8955en

Gallo, L.A., Amico, I., Bozzi, J., Cedres Gazo, M., Cerrillo, T., Datri, L. *et al.* 2020. *Salix humboldtiana*: A very ancient willow and the only native to Argentina. *In* M.J. Pastorino & P. Marchelli, eds*. Low intensity breeding of native forest trees in Argentina: Genetic basis for their domestication and conservation*, pp. 192–216.

Gamba, D. & Muchhala, N. 2020. Global patterns of population genetic differentiation in seed plants. *Molecular Ecology*, 29: 3413–3428. doi: 10.22541/au.158022653.32078930

Gapare, W.J., Aitken, S.N. & Ritland, C.E. 2005. Genetic diversity of core and peripheral Sitka spruce (*Picea sitchensis* (Bong.) Carr) populations: implications for conservation of widespread species. *Biological Conservation*, 123(1): 113–123. doi: 10.1016/j.biocon.2004.11.002

Gapare, W.J. 2013. Merging applied gene conservation activities with advanced generation breeding initiatives: a case study of *Pinus radiata* D. Don. *New Forests*, 45(3): 311–331. doi: 10.1007/s11056-013-9398-0

Garen, E.J., Saltonstall, K., Ashton, M.S., Slusser, J.L., Mathias, S. & Hall, J. S. 2011. The tree planting and protecting culture of cattle ranchers and small-scale agriculturalists in rural Panama: opportunities for reforestation and land restoration. *Forest Ecology and Management*, 261: 1684–1695. doi: 10.1016/j.foreco.2010.10.011

Gauthier, S., Bernier, P., Kuuluvainen, T., Shvidenko, A. Z. & Schepaschenko, D. G. 2015. Boreal forest health and global change. *Science*, 349: 819–822. doi: 10.1126/science.aaa9092

GBIF. 2022. *Global Biodiversity Information Facility*. Copenhagen, GBIF Secretariat. https://www.gbif.org/

Geburek, T. & Myking, T. 2018. Evolutionary consequences of historic anthropogenic impacts on forest trees in Europe. *Forest Ecology and Management*, 422: 23–32. doi: 10.1016/j.foreco.2018.03.055

Gibson, A.L., Espeland, E.K., Wagner, V. & Nelson, C.R. 2016. Can local adaptation research in plants inform selection of native plant materials? An analysis of experimental methodologies. *Evolutionary Applications*, 9(10): 1219–1228. doi: 10.1111/eva.12379

Gómez-Pineda, E., Sáenz-Romero, C., Ortega-Rodríguez, J.M., Blanco-García, A., Madrigal-Sánchez, X., Lindig-Cisneros *et al*. 2020. Suitable climatic habitat changes for Mexican conifers along altitudinal gradients under climatic change scenarios. *Ecological Applications*, 30(2): e02041. doi: 10.1002/eap.2041

González, A.V., Gómez-Silva, V., Ramírez M.J. & Fontúrbel, F.E. 2019. Meta-analysis of the differential effects of habitat fragmentation and degradation on plant genetic diversity. *Conservation Biology,* 34(3): 711–720. doi: 10.1111/cobi.13422

Goodale, U.M., Antonelli, A., Nelson, C.R. & Chau, M.M. 2023. Seed banks needed to restore ecosystems. *Science*, 379: 147. https://www.science.org/doi/10.1126/science.adg2171

Government of Swaziland. 2016. Swaziland's Second National Biodiversity Strategy & Action Plan. [Cited 21 December 2024]. https://www.cbd.int/doc/world/sz/sz-nbsap-v2-en.pdf

Graefe, S., Meyer-Sand, L.F., Chauvette, K., Abdulai, I., Jassogne, L., Vaast, P. & Asare, R. 2017. Evaluating farmers' knowledge of shade trees in different cocoa agro-ecological zones in Ghana. *Human Ecology*, 45: 321–332. doi: 10.1007/s10745-017-9899-0

Grattapaglia, D., Silva-Junior, O.B., Resende, R.T., Cappa, E.P., Müller, B.S., Tan, B., Isik, F. *et al.* 2018. Quantitative genetics and genomics converge to accelerate forest tree breeding. *Frontiers in Plant Science*, 9: 1693. doi: 10.3389/fpls.2018.01693

Grattapaglia, D. 2022. Twelve years into genomic selection in forest trees: climbing the slope of enlightenment of marker assisted tree breeding. *Forests*, 13(10): 1554. doi: 10.3390/f13101554

Graudal, L., Aravanopoulos, F., Bennadji, Z., Changtragoon, S., Fady, B., Kjær, E. D., Loo, J., *et al*. 2014. Global to local genetic diversity indicators of evolutionary potential in tree species within and outside forests. *Forest Ecology and Management,* 333: 35-51. doi: 10.1016/j.foreco.2014.05.002

Graudal, L., Lillesø, J-PB., Dawson, I. K., Abiyu, A., Roshetko, J.M., Nyoka, I., Tsobeng, A. *et al*. 2021. *Tree seed and seedling systems for resilience and productivity*. FTA Highlights of a Decade 2011–2021 Series. Highlight No. 2. Bogor, Indonesia, CGIAR Research Program on Forests, Trees and Agroforestry. doi: 10.17528/cifor/008212

Graudal, L., Dawson, I. K., Hale, I., Powell, W., Hendre, P., & Jamnadass, R. 2022. 'Systems approach'plant breeding illustrated by trees. *Trends in Plant Science*, *27*(2): 158-165. doi: 10.1016/j.tplants.2021.09.009

Gray, L.K., Russell, E.J., Barber, Q.E. & Hamann, A. 2017. Genetic conservation planning for forest tree species in Western North America under future climate change: employing a novel approach to identify conservation gaps. In: R.A. Sniezko, G. Man, V. Hipkins, K. Woeste, D. Gwaze, J.T. Kliejunas *et al.,* eds. *Proceedings of Workshop on Gene Conservation of Tree Species–Banking on the Future*. Portland, USA, US Department of Agriculture, Forest Service, Pacific Northwest Research Station. https://www.fs.usda.gov/treesearch/pubs/55062

Guevara-Andino, J.E., Navas-Muñoz, D. & Endara, M.-J. 2024. High extinction risk of the endemic tree flora in a hyper-diverse region of the Amazon. *Plants, People, Planet*, 1: 1–13. doi: 10.1002/ppp3.10606

Gugger, P.F., Liang, C.T., Sork, V.L., Hodgskiss, P. & Wright, J.W. 2018. Applying landscape genomic tools to forest management and restoration of Hawaiian koa (*Acacia koa*) in a changing environment. *Evolutionary Applications*, 11(2): 231–242. doi: 10.1111/eva.12534

Gullino, M.L., Albajes, R., Al-Jboory, I., Angelotti, F., Chakraborty, S., Garrett, K.A., Hurley, B.P. *et al*. 2022. Climate change and pathways used by pests as challenges to plant health in agriculture and forestry. *Sustainability*, 14: 12421. doi: 10.3390/su141912421

Gumbo, D.J., Dumas-Johansen, M., Muir, G., Boerstler, F. & Xia, Z. 2018. Sustainable management of Miombo woodlands – Food security, nutrition and wood energy. Rome, FAO.

Guo, Q., Fei, S., Potter, K.M., Liebhold, A.M. & Wen, J. 2019. Tree diversity regulates forest pest invasion. *Proceedings of the National Academy of Sciences*, 116(15): 7382–7386. doi: 10.1073/pnas.1821039116

Guo, W.Y., Serra-Diaz, J.M., Schrodt, F., Eiserhardt, W.L., Maitner, B.S., Merow, C. *et al*. 2022. High exposure of global tree diversity to human pressure. *Proceedings of the National Academy of Sciences*, 119(25): e2026733119.

Guo, W.Y., Serra-Diaz, J.M., Eiserhardt, W.L. *et al.* 2023. Climate change and land use threaten global hotspots of phylogenetic endemism for trees. *Nat Commun*, 14: 6950. doi: 10.1038/s41467-023-42671-y

Guo, Z.-H., Ma, P.-F., Yang, G.-Q., Hu, J.-Y., Liu, Y.-L., Xia, E.-H., Zhong, M.-C *et al.* 2019. Genome sequences provide insights into the reticulate origin and unique traits of woody bamboos. *Molecular Plant* 12, 1353–1365. doi: 10.1016/j.molp.2019.05.009

Hall, D., Hallingbäck, H.R. & Wu, H.X. 2016. Estimation of number and size of QTL effects in forest tree traits. *Tree Genetics & Genomes*, 12: 1–17. doi: 10.1007/s11295-016-1073-0

Hamann, A., Smets, P., Yanchuk, A.D. & Aitken, S.N. 2005. An ecogeographic framework for *in situ* conservation of forest trees in British Columbia. *Canadian Journal of Forest Research*, 35(11): 2553–2561. doi: 10.1139/x05-181

Hamelin, R.C. & Roe, A.D. 2020. Genomic biosurveillance of forest invasive alien enemies: A story written in code. *Evolutionary Applications*, 13(1): 95–115. doi: 10.1111/eva.12853

Hamilton, J.A. & Miller, J.M. 2016. Adaptive introgression as a resource for management and genetic conservation in a changing climate. *Conservation Biology*, 30(1): 33–41. doi: 0.1111/cobi.12574

Hamilton, K.N., Offord, C.A., Cuneo, P. & Deseo, M.A. 2013. A comparative study of seed morphology in relation to desiccation tolerance and other physiological responses in 71 eastern Australian rainforest species. *Plant Species Biol*, 28: 51–62. doi: 10.1111/j.1442-1984.2011.00353.x

Hammond, W.M., Williams, A.P., Abatzoglou, J.T., Adams, H.D., Klein, T., López, R., Sáenz-Romero, C. *et al*. 2022. Global field observations of tree die-off reveal hotter-drought fingerprint for Earth’s forests. *Nature Communications*, 13(1): 1–11. doi: 10.1038/s41467-022-29289-2

Hamrick, J.L. 1978. Genetic variation and longevity. *In* O.T Solbrig, S. Jain, G.B. Johnson and P. H. Raven, eds. *Plant Population Biology*, pp 84–113. New York, Columbia University Press.

Hamrick, J.L. & Godt, M.J.W. 1996. Effects of life history traits on genetic diversity in plant species. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 351: 1291–1298. doi: 10.1098/rstb.1996.0112

Hamrick, J.L., Godt, M.J.W. & Sherman-Broyles, S.L. 1992. Factors influencing levels of genetic diversity in woody plant species. In *Population Genetics of Forest Trees: Proceedings of the International Symposium on Population Genetics of Forest Trees Corvallis, Oregon, USA, July 31–August 2, 1990* (pp. 95-124). Springer Netherlands.In *Population genetics of forest trees*, 95–124. Dordrecht, Springer. doi: 10.1007/bf00120641

Hand, B.K., Lowe, W.H., Kovach, R.P., Muhlfeld, C.C. & Luikart, G. 2015. Landscape community genomics: understanding eco-evolutionary processes in complex environments. *Trends in Ecology & Evolution*, 30(3): 161–168. doi: 10.1016/j.tree.2015.01.005

Hannah, L., Midgley, G., Andelman, S., Araújo, M., Hughes, G., Martinez-Meyer, E. *et al*. 2007. Protected area needs in a changing climate. *Frontiers in Ecology and the Environment*, 5(3): 131–138. doi: 10.1890/1540-9295(2007)5[131:PANIAC]2.0.CO;2

Hansen, J., Sato, M. & Ruedy, R. 2022. *Drier dryspots, wetter wetspots, and stronger storms; April 2022 temperature update.* Climate Science, Awareness and Solution Programs Communications. 16 May 2022. New York, USA, Columbia University.

http://www.columbia.edu/~jeh1/mailings/2022/AprilTemperatureUpdate.16May2022.pdf

Hansen, J. 2024. *Climate Change at the International Court of Justice.* Climate Science, Awareness and Solution Programs Communications. 09 December 2024. New York, USA, Columbia University. https://www.columbia.edu/~jeh1/mailings/2024/ICJ.PressBriefing.09December2024.pdf

Hardy, O.J., Maggia, L., Bandou, E., Breyne, P., Caron, H., Chevallier, M.H. *et al*. 2006. Fine-scale genetic structure and gene dispersal inferences in 10 Neotropical tree species. *Molecular ecology*, *15*(2), pp.559-571. doi: 10.1111/j.1365-294x.2005.02785.x

Hardy, O.J., Born, C., Budde, K., Daïnou, K., Dauby, G., Duminil, J., Ewédjé, E.B.K. *et al*. 2013. Comparative phylogeography of African rain forest trees: a review of genetic signatures of vegetation history in the Guineo-Congolian region. *Comptes Rendus Geoscience*, 345(7–8): 284–296. doi: 10.1016/j.crte.2013.05.001

Haristoy, G., Bouffier, L., Fontes, L., Leal, L., Paiva, J. A., Pina, J. P. & Gion, J. M. 2023. Genomic prediction in a multi-generation *Eucalyptus globulus* breeding population. *Tree Genetics & Genomes*, *19*(1): 8. doi: 10.1007/s11295-022-01579-2

Harris, J.A., Hobbs, R.J., Higgs, E. & Aronson, J. 2006. Ecological restoration and global climate change. *Restoration Ecology*, 14 (2): 170–176. doi: 10.1111/j.1526-100X.2006.00136.x

Harrison, R.D., Shono, K., Gitz, V., Meybeck, A., Hofer, T. & Wertz-Kanounnikoff, S. 2022. *Mainstreaming biodiversity in forestry*. FAO Forestry Paper No. 188. Rome, FAO, and Bogor, Indonesia, CIFOR. doi: 10.4060/cc2229en

Harsh, N.S.K., Chandra, S. & Uniyal, K. 2011. Screening resistance of *Dalbergia sissoo* clones against *Ganoderma lucidum* root rot disease in field conditions. *Forest Pathology*, 41(3): 221–226. doi: 10.1111/j.1439-0329.2010.00685.x

Hartvig, I., So, T., Changtragoon, S., Tran, H.T., Bouamanivong, S., Ogden, R., Senn, H. *et al*. 2020. Conservation genetics of the critically endangered Siamese rosewood (*Dalbergia cochinchinensis*): Recommendations for management and sustainable use. *Conservation Genetics*, 21(4): 677–692. doi: 10.1007/s10592-020-01279-1

Harvey, C.A. & Haber, W.A. 1998. Remnant trees and the conservation of biodiversity in Costa Rican pastures. *Agroforestry Systems*, 44: 37–68. doi: 10.1023/A:1006122211692

Hassan, M.M. 2017. *In vitro* conservation of date palm somatic embryos using growth-retardant conditions. *Methods Mol Biol*, 1638: 61–70. doi: 10.1007/978-1-4939-7159-6_6/cover

Healey, A.L., Shepherd, M., King, G.J., Butler, J.B.B., Freeman, J.S., Lee, D.J., *et al*. 2021. Pests, diseases, and aridity have shaped the genome of *Corymbia citriodora*. *Communications Biology*, 4: 537. doi: 10.1038/s42003-021-02009-0

Hendre, P.S., Graudal, L., Kindt, R., Hale, I., Powell, W., Jamnadass, R., Thomson, L. & Dawson, I.K. 2022. Operationalizing an innovative systems approach for breeding agroforestry trees. CIFOR-ICRAF Infobrief No. 378. Nairobi, Kenya: World Agroforestry. doi: 10.17528/cifor/008758

Hernández-García, H., Ambriz-Parra, E., López-Albarrán, P., Leon, J.D. & Salagado-Garciglia, R. 2021. *In vitro* propagation from axillary buds of the endangered tree *Dalbergia congestiflora* Pittier (Fabaceae). *Plant Biotechnol*, 38: 409–414. doi: 10.5511/plantbiotechnology.21.0901a

Herzog, F. 1994. Multipurpose shade trees in coffee and cocoa plantations in Cote d'Ivoire. *Agroforestry Systems*, 27: 259–267. doi: 10.1007/BF00705060

Heuertz, M., Duminil, J., Dauby, G., Savolainen, V. & Hardy, O.J. 2014. Comparative phylogeography in rainforest trees from Lower Guinea, Africa. *PLoS ONE*, 9(1): e84307. doi: 10.1371/journal.pone.0084307

Hewitt, G. 2000. The genetic legacy of the Quaternary ice ages. *Nature*, 405: 907–913. doi: 10.1038/35016000

Hewitt, N., Klenk, N., Smith, A.L., Bazely, D.R., Yan, N., Wood, S., MacLellan, J.I. *et al*. 2011. Taking stock of the assisted migration debate. *Biological Conservation*, 144(11): 2560–2572. doi: 10.1016/j.biocon.2011.04.031

Hickey, G.M., Pouliot, M., Smith-Hall, C., Wunder, S. & Nielsen, M.R. 2016. Quantifying the economic contribution of wild food harvests to rural livelihoods: a global-comparative analysis. *Food Policy*, 62: 122–132. doi: 10.1016/j.foodpol.2016.06.001

Hirao, A. S., Watanabe, M., Tsuyuzaki, S., Shimono, A., Li, X., Masuzawa, T. & Wada, N. 2017. Genetic diversity within populations of an arctic–alpine species declines with decreasing latitude across the Northern Hemisphere. *Journal of Biogeography*, 44: 2740–2751. doi: 10.1111/jbi.13085

Hitt, R.G. 1952. Forest tree breeding in Sweden and other European countries. *Journal of Forestry*, 50(12): 924–928. doi: 10.1093/jof/50.12.924

Hoban, S., Kelley, J.L., Lotterhos, K.E., Antolin, M.F., Bradburd, G., Lowry, D.B., Poss, M.L., Reed, L.K., Storfer, A. & Whitlock, M.C. 2016. Finding the genomic basis of local adaptation: pitfalls, practical solutions, and future directions. *The American Naturalist*, 188(4): 379–397. doi: 10.1086/688018

Hoban, S., Bruford, M., D'Urban Jackson, J., Lopes-Fernandes, M., Heuertz, M., Hohenlohe, P.A. *et al*. 2020. Genetic diversity targets and indicators in the CBD post-2020 Global Biodiversity Framework must be improved. *Biological Conservation*, 248: 108654. doi: 10.1016/j.biocon.2020.108654

Hoban, S., Campbell, C.D., da Silva, J.M., Ekblom, R., Funk, W.C., Garner, B.A., Godoy, J.A. *et.al*. 2021a. Genetic diversity is considered important but interpreted narrowly in country reports to the Convention on Biological Diversity: Current actions and indicators are insufficient. *Biological Conservation*, 261: 109233. doi: 10.1016/j.biocon.2021.109233

Hoban, S., Paz-Vinas, I., Aitken, S., Bertola, L., Breed, M.F., Bruford, M. *et al.* 2021. Effective population size remains a suitable, pragmatic indicator of genetic diversity for all species, including forest trees. *Biological Conservation*, 253: 108906. doi: 10.1016/j.biocon.2020.108906 v

Hoban S., Bruford M.W., da Silva J.M., Funk W.C., Frankham R., Gill, M.J., Grueber, C.E. *et.al*. 2023. Genetic diversity goals and targets have improved, but remain insufficient for clear implementation of the post-2020 global biodiversity framework. *Conservation Genetics*, 24: 181–191. doi: 10.1007/s10592-022-01492-0

Holliday, J.A., Aitken, S.N., Cooke, J.E., Fady, B., González-Martínez, S.C., Heuertz, M., Jaramillo-Correa, J.P. *et al*. 2017. Advances in ecological genomics in forest trees and applications to genetic resources conservation and breeding. *Molecular Ecology*, 26(3): 706–717. doi: 10.1111/

mec.13963

Hollingsworth, P.M., O'Brien, D., Ennos, R.A., Yahr, R., Neaves, L., Ahrends, A., Ballingall *et al.* 2020. Scotland's Biodiversity Progress to 2020 Aichi Targets: Conserving Genetic Diversity– Development of a national approach for addressing Aichi Biodiversity Target 13 that includes wild species.

Horgan, R. P., & Kenny, L. C. 2011. ‚Omic' technologies: genomics, transcriptomics, proteomics and metabolomics. *Obstetrician & Gynaecologist*, *13*(3). doi: 10.1576/toag.13.3.189.27672

Hosonuma, N., Herold, M., De Sy, V., De Fries, R., Brockhaus, M., Verchot, L., Angelsen, A. & Romijn, E. 2012. An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters*, 7(4): 044009. doi: 10.1088/1748-9326/7/4/044009

Hu, S., Dilcher, D.L., Jarzen, D.M. & Winship Taylor, D. 2008. Early steps of angiosperm–pollinator coevolution. *Proceedings of the National Academy of Sciences*, 105(1): 240–245. doi: 10.1073/pnas.0707989105

Hu, Z.-M., Zhong, K.-L., Weinberger, F., Duan, D.-L., Draisma, S. G. A. & Serrão, E. A. 2020. Linking Ecology to Genetics to Better Understand Adaptation and Evolution: A Review in Marine Macrophytes. *Frontiers in Marine Science*, 7. doi: 10.3389/fmars.2020.545102

Hung, T.H., So, T., Sreng, S., Thammavong, B., Boounithiphonh, C., Boshier, D.H., & MacKay, J J. 2020. Reference transcriptomes and comparative analyses of six species in the threatened rosewood genus *Dalbergia*. *Scientific Reports*, 10: 17749. doi: 10.1038/s41598-020-74814-2

Hung, T. H., So, T., Thammavong, B., Chamchumroon, V., Theilade, I., Phourin, C., Bouamanivong, S. *et al.* 2023. Range-wide differential adaptation and genomic offset in critically endangered Asian rosewoods. *Proceedings of the National Academy of Sciences*, *120*(33), e2301603120. doi: 10.1073/pnas.2301603120

Hunt, D.R. 1996. The genera of temperate broadleaved trees. *Broadleaves*, 2: 4–5.

Ickowitz, A., McMullin, S., Rosenstock, T., Dawson, I., Rowland, D., Powell, B., Mausch, K. *et al.* 2022. Transforming food systems with trees and forests. *Lancet Planet Health*, 6: e632–e639. doi: 10.1016/s2542-5196(22)00091-2

ICRAF. n.d. Tree seed suppliers directory | World Agroforestry | transforming lives and landscapes with trees [accessed 26 November 2024]. https://www.worldagroforestry.org/output/tree-seed-suppliers-directory

IEA, IRENA, UN, World Bank & WHO. 2021. Tracking SDG7: The Energy Progress Report 2021. Washington, DC, World Bank.

Imai, R., Tsuda, Y., Matsumoto, S., Ebihara, A. & Watano, Y. 2016. The relationship between mating system and genetic diversity in diploid sexual populations of *Cyrtomium falcatum* in Japan. *PLoS ONE*, 11, e0163683. doi: 10.1371/journal.pone.0163683

INBAR. 2023. *International Network of Bamboo and Rattan*. Cited 5 February 2023. https://www.inbar.int/resources/.

Ingvarsson, P. K. & Bernhardsson, C. 2020. Genome-wide signatures of environmental adaptation in European aspen (*Populus tremula*) under current and future climate conditions. *Evolutionary Applications*, 13: 132–142. doi: 10.1111/eva.12792

IUCN. 2012. *IUCN Red List Categories and Criteria: Version 3.1. Second edition*. Gland, Switzerland and Cambridge, UK.

IUCN. 2024. IUCN Red List of Threatened Species. [Cited 20 December 2024]. https://www.iucnredlist.org/

IUCN Standards and Petitions Committee. 2024. Guidelines for Using the IUCN Red List Categories and Criteria. Version 16. https://www.iucnredlist.org/documents/RedListGuidelines.pdf

IPBES. 2016*. Summary for policymakers of the assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production*. Secretariat of the Intergovernmental Science-Policy Platform on

Biodiversity and Ecosystem Services, Bonn.

IPBES. 2019. *Summary for policymakers of the global assessment report on biodiversity and ecosystem services*. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn.

IPCC (Intergovernmental Panel on Climate Change). 2022a. *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge, UK and New York, USA, Cambridge University Press. 3056 pp. doi:10.1017/9781009325844

IPCC. 2022b. Summary for policymakers. In: *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, pp. 3–34. Cambridge, Cambridge University Press. doi: 10.1017/9781009325844.001.

IPCC. 2023. *Climate Change 2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, H. Lee & J. Romero, eds. Geneva, Switzerland. doi: 10.59327/IPCC/AR6-9789291691647.

Ipinza Carmona, R., González Campos, J., Molina Brand, M., Gutiérrez Caro, B., Soto Guevara, H., Koch Zúñiga, L., Hasbún Zaror, R. *et al*. 2022. Migración asistida de *Araucaria araucana*, un estudio de caso en Chile. *Ciencia & Investigación Forestal*, *28*(2): 21–32. doi:10.52904/0718-4646.2022.566

Isabel, N., Holliday, J. A. & Aitken, S. N. 2020. Forest genomics: Advancing climate adaptation, forest health, productivity, and conservation. *Evolutionary Applications*, 13: 3–10. doi: 10.1111/eva.12902

Isik, F. 2014. Genomic selection in forest tree breeding: the concept and an outlook to the future. *New Forests*, 45(3): 379–401. doi: 10.1007/s11056-014-9422-z

IUCN (International Union for Conservation of Nature and Natural Resources). 2012. *IUCN Red List Categories and Criteria: Version 3.1. Second edition*. Gland, Switzerland and Cambridge, UK.

IUCN. 2023. *IUCN Red List of Threatened Species. 2023.1*. Gland, Switzerland. www.iucnredlist.org

IUCN. Undated. IUCN Red List of Threatened Species. [Cited 20 December 2024]. https://www.iucnredlist.org/

IUCN-WCPA Task Force on OECMs. 2019. *Recognising and reporting other effective area-based conservation measures*. World Commission on Protected Areas Task Force on OECMs, Gland, Switzerland. https://portals.iucn.org/library/node/48773

IUFRO (International Union of Forest Research Organizations). 2020. *IUFRO Post-2020 Strategy*. [Cited 26 September 2024]. https://www.iufro.org/media/fileadmin/publications/general-publications/iufro-strategy-2020-post.pdf

IUFRO. 2023. *Interconnecting forests, science and people.* [Cited 23 January 2024]. https://www.iufro.org/discover/strategy/

Jackson, N.D. & Fahrig, L. 2014. Landscape context affects genetic diversity at a much larger spatial extent than population abundance. *Ecology*, 95(4): 871–881. doi: 10.1890/13-0388.1

Jactel, H., Moreira, X. & Castagneyrol, B. 2021. Tree diversity and forest resistance to insect pests: patterns, mechanisms, and prospects. *Annual Review of Entomology*, 66: 277–296. doi: 10.1146/annurev-ento-041720-075234

Jain, P., Castellanos-Acuna, D., Coogan, S.C.P., Abatzoglou J.T. & Flannigan M.D. 2022. Observed increases in extreme fire weather driven by atmospheric humidity and temperature. *Nature Climate Change,* 12(1): 63–70. doi: 10.1038/s41558-021-01224-1

Jalonen, R., Valette, M., Boshier, D., Duminil, J. & Thomas, E. 2018. Forest and landscape restoration severely constrained by a lack of attention to the quantity and quality of tree seed: insights from a global survey. *Conserv Lett*, 11: *e12424*. doi: 10.1111/conl.12424

Jalonen, R., Yongqi, Z. & Warrier, R.R. 2024. *APFORGEN secures $1.48M to protect vital Asian tree species.* Rome, Bioversity International, and Cali, Colombia, CIAT. https://alliancebioversityciat.org/publications-data/apforgen-secures-148m-protect-vital-asian-tree-species

Jalonen, R., Gaisberger, H., Fremout, T., Bounithiphonh, C., Kettle, C. 2024. *Asian rosewoods now critically endangered on IUCN Red List.* Rome, Bioversity International and Cali, Colombia. CIAT. https://alliancebioversityciat.org/publications-data/asian-rosewoods-now-critically-endangered-iucn-red-list

Jansen, M., Guariguata, M.R., Raneri, J.E., Ickowitz, A., Chiriboga-Arroyo, F., Quaedvlieg, J. & Kettle, C.J. 2020. Food for thought: The underutilized potential of tropical tree-sourced foods for 21st century sustainable food systems. *People and Nature*, 2: 1006–1020. doi: 10.1002/pan3.10159

Janzen, D. 1976. Why bamboos wait so long to flower. *Annual Review of Ecology and Systematics*, 7: 347–391. doi: 10.1146/annurev.es.07.110176.002023

Jaramillo-Correa, J.P., Beaulieu, J., Khasa, D.P. & Bousquet, J. 2009. Inferring the past from the present phylogeographic structure of North American forest trees: seeing the forest for the genes. *Canadian Journal of Forest Research*, 39(2): 286–307. doi: 10.1139/x08-181

Jeník, J. 1994. Clonal growth in woody plants: a review. *Folia Geobotanica*, 29: 291–306. doi: 10.1007/bf02803802

Jepson, P. & Arakelyan, I. 2017. Exploring public perceptions of solutions to tree diseases in the UK: Implications for policy-makers. *Environmental Science & Policy*, 76: 70–77. doi: 10.1016/j.envsci.2017.06.008

Jiang, W., Yang, S., Yang, X. & Gu, N. 2016. Negative impacts of afforestation and economic forestry on the Chinese Loess Plateau and proposed solutions. *Quat Int*, 399: 165–173. doi: 10.1016/j.quaint.2015.04.011

Jiang, Y., Guo, L., Ma, X., Zhao, X., Jiao, B., Li, C. & Luo, K. 2017. The WRKY transcription factors PtrWRKY18 and PtrWRKY35 promote Melampsora resistance in Populus. *Tree Physiology*, 37, 665–675. doi: 10.1093/treephys/tpx008

Johnson, D.V. & Sunderland, T.C.H. 2004. *Non-wood forest products 16: Rattan glossary compendium glossary with emphasis on Africa*. Rome, FAO.

Jones, A.M. & Saxena, P.K. 2013. Inhibition of phenylpropanoid biosynthesis in *Artemisia annua* L.: a novel approach to reduce oxidative browning in plant tissue culture. *PLoS One*, 8: e76802. doi: 10.1371/journal.pone.0076802

Jones, B. 2021. The surprising downsides to planting trillions of trees. Vox. https://www.vox.com/down-to-earth/22679378/tree-planting-forest-restoration-climate-solutions

Juan-Vicedo, J., Serrano-Martínez, F., Cano-Castillo, M., & Casas, J. L. 2022. In vitro propagation, genetic assessment, and medium-term conservation of the coastal endangered species *Tetraclinis articulata* (Vahl) Masters (Cupressaceae) from adult trees. *Plants*, *11*(2), 187. https://doi.org/10.3390/plants11020187

Judziewicz, E.J., Clark, L.G., Londono, X. & Stern, M.J. 1999. *American bamboos*. Washington, DC, Smithsonian Institution Press.

Kanjana, N., Li, Y., Shen, Z., Mao, J. & Zhang, L. 2024. Effect of phenolics on soil microbe distribution, plant growth, and gall formation. *Sci Total Environ*, 924: 171329. doi: 10.1016/j.scitotenv.2024.171329

Kaplan, J. O., Bigelow, N. H., Prentice, I. C., Harrison, S. P., Bartlein, P. J., Christensen, T. R., Cramer, W, *et al.* 2003. Climate change and Arctic ecosystems: 2. Modeling, paleodata-model comparisons, and future projections. *Journal of Geophysical Research: Atmospheres*, 108(D19). doi: 10.1029/2002jd002559

Kapoor, B., Jenkins, J., Schmutz, J., Zhebentyayeva, T., Kuelheim, C., Coggeshall, M., Heim, C. *et al*. 2023. A haplotype-resolved chromosome-scale genome for *Quercus rubra* L. provides insights into the genetics of adaptive traits for red oak species. *G3: Genes, Genomes, Genetics*, 13(11). doi: 10.1093/g3journal/jkad209

Karambiri, M., Elias, M., Vinceti, B. & Grosse, A. 2017. Exploring local knowledge and preferences for shea (*Vitellaria paradoxa*) ethnovarieties in Southwest Burkina Faso through a gender and ethnic lens. *Forests, Trees and Livelihoods*, 26(1): 13–28. doi: 10.1080/14728028.2016.1236708

Kardos, M., Taylor, H.R., Ellegren, H., Luikart, G. & Allendorf, F.W. 2016. Genomics advances the study of inbreeding depression in the wild. *Evolutionary Applications*, 9(10): 1205-1218. doi: 10.1111/eva.12414

Katila, P., Colfer, C.J.P., de Jong, W., Galloway, G., Pacheco, P., Winkel, G. eds. 2019. *Sustainable Development Goals: Their Impacts on Forests and People*. Cambridge, Cambridge University Press. doi: 10.1017/9781108765015

Kawecki, T. J. & Ebert, D. 2004. Conceptual issues in local adaptation. *Ecology Letters*, 7(12): 1225–1241. doi: 10.1111/j.1461-0248.2004.00684.x

Kazana, V., Tsourgiannis, L., Iakovoglou, V., Stamatiou, C., Alexandrov, A., Araújo, A., Bogdan, S. *et al.* 2015. Public attitudes towards the use of transgenic forest trees: a cross-country pilot survey. *iForest-Biogeosciences and Forestry*, 9(2): 344-353. doi: 10.3832/ifor1441-008

Keesing, F., Belden, L.K., Daszak, P., Dobson, A., Harvell, C.D., Holt, R.D., Hudson, P. *et al*. 2010. Impacts of biodiversity on the emergence and transmission of infectious diseases. *Nature*, 468(7324): 647–652. doi: 10.1038/nature09575

Kehlenbeck, K., Kindt, R., Sinclair, F.L., Simons, A.J. & Jamnadass, R. 2011. Exotic tree species displace indigenous ones on farms at intermediate altitudes around Mount Kenya. *Agroforestry Systems*, 83: 133–147. doi: 10.1007/s10457-011-9413-4

Keith, D. A., Ferrer-Paris, J. R., Nicholson, E., Bishop, M. J., Polidoro, B. A., Ramirez-Llodra, E., Tozer, M. G. 2022. A function-based typology for Earth's ecosystems. *Nature*, 610(7932): 513–518.

Kelleher, C.T., de Vries, S.M.G., Baliuckas, V., Bozzano, M., Frýdl, J., Gonzalez Goicoechea, P., Ivankovic, M. *et al.* 2015. Approaches to the conservation of forest genetic resources in Europe in the Context of Climate Change. European Forest Genetic Resources Programme (EUFORGEN). Rome, Bioversity International.

Kelleher, C.T. 2018. Evolution and conservation of trees–a review of salient issues. *Annual Plant Reviews online*, 355–380. doi: 10.1002/9781119312994.apr0621

Keller, D., Holderegger, R., van Strien, M.J. & Bolliger, J. 2015. How to make landscape genetics beneficial for conservation management? *Conservation Genetics*, 16(3): 503-512. doi: 10.1007/s10592-014-0684-y

Kellogg, E. 2015. *Poaceae.* Vol. XIII, Families and Genera of Flowering Plants. K. Kubitzki, ed. Cham, Switzerland, Springer. doi: 10.1007/978-3-319-15332-2

Kenrick, P. & Crane, P.R. 1997. The origin and early evolution of plants on land. *Nature*, 389(6646): 33–39. doi: 10.1038/37918

Kettle, C.J. 2012. Seeding ecological restoration of tropical forests: priority setting under REDD+. *Biol Conserv*, 154: 34–41. doi: 10.1016/j.biocon.2012.03.016

Khoury, C.K., Brush, S., Costich, D.E., Curry, H.A., Haan, S., Engels, J.M.M. *et al*. 2022. Crop genetic erosion: understanding and responding to loss of crop diversity. *New Phytologist*, 233: 84–118. doi: /10.1111/nph.17733

Kindt, R., Mutua, A., Muasya, S.N. & Kimotho, J. 2002. Tree seed suppliers directory: sources of seeds and microsymbionts. Nairobi, Kenya: World Agroforestry.

Kindt, R., Dawson, I., Graudal, L. & Jamnadass, R. 2021. *The Global Tree Knowledge Platform: a collection of interlinked databases, maps, guidelines, R packages and other decision-support tools to guide planting of the 'right tree in the right place for the right purpose'*. Nairobi, World Agroforestry. www.worldagroforestry.org/tree-knowledge

Kindt, R., John, I., Dawson, I.K., Graudal, L., Lillesø,

J-P.B., Ordonez, J. & Jamnadass, R. 2022. *Agroforestry Species Switchboard: a synthesis of information sources to support tree research and development activities*. Version 3.0. Nairobi, CIFOR-ICRAF. https://www.worldagroforestry.org/output/agroforestry-species-switchboard-30

Kindt, R., Graudal, L., Lillesø, J.B., Pedercini, F., Smith, P. & Jamnadass, R. 2023. GlobalUsefulNativeTrees, a database of 14,014 tree species and their uses, supports synergies between biodiversity recovery and local livelihoods in landscape restoration. *Scientific Reports,* 13:article 12640. doi: 10.1038/s41598-023-39552-1

Kindt, R. 2023. TreeGOER: A database with globally observed environmental ranges for 48,129 tree species. *Global Change Biology*, 29: 6303–6318. doi: 10.1111/gcb.16914

Kindt, R., Graudal, L., Lillesø, J-P., Pedercini, F., Smith, P. & Jamnadass, R. 2024. GlobalUsefulNativeTrees: country-specific selections of native tree species for forest landscape restoration and biodiverse plantings. [Cited 10 May 2024]. https://patspo.shinyapps.io/GlobalUsefulTrees

Kissinger, G., Herold, M. & De Sy, V. 2012. *Drivers of deforestation and forest degradation: A synthesis report for REDD+ policymakers*. Vancouver, Canada, Lexeme Consulting.

Klein, A.M., Vaissiere, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C. & Tscharntke, T. 2007. Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences*, 274: 303–313. doi: 10.1098/rspb.2006.3721

Kling, M. M. & Ackerly, D. D. 2021. Global wind patterns shape genetic differentiation, asymmetric gene flow, and genetic diversity in trees. *Proceedings of the National Academy of Sciences*, 118(17): e2017317118. doi: 10.1073/pnas.2017317118

Koelewijn, H. P., Koski, V. & Savolainen, O. 1999. Magnitude and timing of inbreeding depression in Scots pine (*Pinus sylvestris* L.). *Evolution*, 53(3): 758–768. doi: 10.2307/2640716

König, A.O. 2005. Provenance research: evaluating the spatial pattern of genetic variation. In: T. Geburek & J. Turok, eds. *Conservation and management of forest genetic resources in Europe*, pp. 275–333. Zvolen, Slovakia, Arbora Publishers.

Konnert, M., Maurer, W., Degen, B. & Kätzel, R. 2011. Genetic monitoring in forests—early warning and controlling system for ecosystematic changes. *iForest*, 4(2): 77–81. doi: 10.3832/ifor0571-004

Koskela, J., Lefèvre, F., Schueler, S., Kraigher, H., Olrik, D.C., Hubert, J. *et al*. 2013. Translating conservation genetics into management: Pan-European minimum requirements for dynamic conservation units of forest tree genetic diversity. *Biological Conservation*, 157: 39–49. doi: 10.1016/j.biocon.2012.07.023

Koskela, J., Vinceti, B., Dvorak, W., Bush, D., Dawson, I. K., Loo, J., Kjær, E.D. *et al*. 2014. Utilization and transfer of forest genetic resources: A global review. *Forest Ecology and Management*, 333: 22–34. doi: 10.1016/j.foreco.2014.07.017

Kowarik, I., Hiller, A., Planchuelo, G., Seitz, B., von der Lippe, M. & Buchholz, S. 2019. Emerging urban forests: opportunities for promoting the wild side of the urban green infrastructure. *Sustainability*, 11: article 6318. doi: 10.3390/su11226318

Kpolita, A., Dubiez, E., Yongo, O. & Peltier, R. 2022. First evaluation of the use of assisted natural regeneration by Central African farmers to restore their landscapes. *Trees, Forests and People*, 7: article 100165. doi: 10.1016/j.tfp.2021.100165

Krishnan, S., Wiederkehr Guerra, G., Bertrand, D., Wertz-Kanounnikoff, S. & Kettle, C.J. 2020. *The pollination services of forests – A review of forest and landscape interventions to enhance their cross-sectoral benefits*. Forestry Working Paper No. 15. Rome, FAO & Bioversity International.

Kung'u, J.B., Muchiri, B.K. & Kuria, A. 2021. *Regional Assessment of Forest Education in Africa*. Rome, FAO. https://www.fao.org/3/cb6733en/cb6733en.pdf

Kurek, K., Plitta-Michalak, B. & **Ratajczak, E.** 2019. Reactive oxygen species as potential drivers of the seed aging process. *Plants*, 8: 174. doi: 10.3390/plants8060174

Laikre, L. 2010. Genetic diversity is overlooked in international conservation policy implementation. *Conservation Genetics*, 11: 349–354. doi: 10.1007/s10592-009-0037-4

Laikre, L., Allendorf, F. W., Aroner, L. C., Baker, C. S., Gregovich, D. P., Hansen, M. M., Jackson *et al*. 2010. Neglect of genetic diversity in implementation of the Convention of Biological Diversity. *Conservation Biology*, 24: 86–88.

Lan, Q. Y., Xia, K., Wang, X. F., Liu, J. W., Zhao, J., & Tan, Y. H. 2014. Seed storage behaviour of 101 woody species from the tropical rainforest of southern China: a test of the seed-coat ratio–seed mass (SCR–SM) model for determination of desiccation sensitivity. *Australian Journal of Botany*, 62: 305–311. doi: 10.1071/bt14037

Lander, T.A., Klein, E.K., Stoeckel, S., Mariette, S., Musch, B. & Oddou-Muratorio, S., 2013. Interpreting realized pollen flow in terms of pollinator travel paths and land-use resistance in heterogeneous landscapes. *Landscape Ecology*, 28: 1769–1783. doi: 10.1007/s10980-013-9920-y

Lapola, D.M., Pinho, P., Barlow, J., Aragão, L.E., Berenguer, E., Carmenta, R. & Liddy, H.M. *et al*. 2023. The drivers and impacts of Amazon forest degradation. *Science*, 379(6630): 8622. doi: 10.1126/science.abp862

Ledig, F.T. 1986. Conservation strategies for forest gene resources. *Forest Ecology and Management*, 14: 77–90. doi: 10.1016/0378-1127(86)90093-9

Ledig, F.Th. & Kitzmiller, J.H. 1992. Genetic strategies for reforestation in the face of global climate change. *Forest Ecology and Management*, 50(1-2): 153–169. doi: 10.1016/0378-1127(92)90321-Y

Lefèvre, F., Alia, R., Bakkebø Fjellstad, K., Graudal, L., Oggioni, S.D., Rusanen, M., Vendramin, G.G. & Bozzano, M. 2020. *Dynamic conservation and utilization of forest tree genetic resources: indicators for in situ and ex situ genetic conservation and forest reproductive material*. European Forest Genetic Resources Programme (EUFORGEN), European Forest Institute. https://hdl.handle.net/10568/113426

Lenoir, J., Gégout, J.C., Marquet, P.A., de Ruffray, P. & Brisse, H. 2008. A significant upward shift in plant species optimum elevation during the 20th century. *Science*, 320(5884): 1768–1771. https://www.science.org/doi/10.1126/science.1156831

Lesica, P. & Allendorf, F.W. 1995. When are peripheral populations valuable for conservation? *Conservation biology*, 9(4): 753–760. doi: 10.1046/j.1523-1739.1995.09040753.x

Levis, C., Costa, F.R.C., Bongers, F., Peña-Claros, M., Clement, C.R., Junqueira, A.B., Neves, E.G. *et al*. 2017. Persistent effects of pre-Columbian plant domestication on Amazonian forest composition. *Science*, 355(6328), 925–931. doi: 10.1126/science.aal0157

Li, D., Li, Y., Qian, J., Liu, X., Xu, H., Zhang, G., Ren, J. *et al.* 2021. Comparative transcriptome analysis revealed candidate genes potentially related to desiccation sensitivity of recalcitrant *Quercus variabilis* seeds. *Frontiers of Plant Scince*, 12: 717563. doi: 10.3389/fpls.2021.717563

Li, W., Liu, J., Zhang, H., Liu, Z., Wang, Y., Xing, L., He, Q. & Du, H. 2022. Plant pan-genomics: recent advances, new challenges, and roads ahead. *Journal of Genetics and Genomics*, 49: 833–846. doi: 10.1016/j.jgg.2022.06.004

Li, Y., Mei, B., Linhares-Juvenal, T., Formenton Cardoso, N. & Tshering, C. 2022. *Forest sector contribution to national economies 2015 – The direct, indirect and induced effects on value added, employment and labour income*. Forestry Working Paper No. 33. Rome, FAO. doi: 10.4060/cc2387en

Lillesø, J.-P.B., Harwood, C., Derero, A., Graudal, L., Roshetko, J.M., Kindt, R., Moestrup, S. *et al*. 2018. Why institutional environments for agroforestry seed systems matters. *Development Policy Review*, 36: O89-O112. doi: 10.1111/dpr.12233

Lima, J.S., Ballesteros-Mejia, L., Lima-Ribeiro, M.S. & Collevatti, R.G. 2017. Climatic changes can drive the loss of genetic diversity in a Neotropical savanna tree species. *Global Change Biology*, 23(11): 4639–4650. doi: 10.1111/

gcb.13685

Lima, M. de J., Hong, T.D., Arruda, Y.M.B.C. *et al.* 2014. Classification of seed storage behaviour of 67 Amazonian tree species. *Seed Sci Technol*, 42: 363–392. doi: 10.15258/sst.2014.42.3.06

Lippe, R.S., Schweinle, J., Cui, S., Gurbuzer, Y., Katajamäki, W., Villarreal-Fuentes, M. & Walter, S. 2022. *Contribution of the forest sector to total employment in national economies - Estimating the number of people employed in the forest sector*. Rome and Geneva, FAO and ILO. doi: 10.4060/cc2438en

Liu, J.J., Sniezko, R., Murray, M., Wang, N., Chen, H., Zamany, A. *et al.* 2016. Genetic diversity and population structure of whitebark pine (*Pinus albicaulis* Engelm.) in Western North America. *PLoS ONE*, 11(12). doi: 10.1371/journal.pone.0167986

López Lauenstein, D., Teich, I., Carloni, E., Melchiorre, M., Sagadin, M., Frassoni, J. & Joseau, M.J. 2021. Genetic breeding of *Prosopis* species from the "Great American Chaco". In: M.J. Pastorino & P. Marchelli, eds. *Low intensity breeding of native forest trees in Argentina*: *Genetic basis for their domestication and conservation,* pp. 271-293. Cham, Switzerland, Springer. doi: 10.1007/978-3-030-56462-9

López-Gómez, A.M., Williams-Linera, G. & Manson, R.H. 2008. Tree species diversity and vegetation structure in shade coffee farms in Veracruz, Mexico. *Agriculture, Ecosystems and Environment*, 124: 160–172. doi: 10.1016/j.agee.2007.09.008

López-Toledo, L., Heredia-Hernández, M., Castellanos-Acuna, D., Blanco-García, A. & Saénz-Romero, C. 2017. Reproductive investment of *Pinus pseudostrobus* along an altitudinal gradient in Western Mexico: implications of climate change. *New Forests*, 48(6): 867–881. doi: 10.1007/s11056-017-9602-8

Loveless, M. D. 1992. Isozyme variation in tropical trees: patterns of genetic organization. *New Forests*, 6: 67–94. doi: 10.1007/bf00120640

Lovrić, M., Da Re, R., Vidale, E., Prokofieva, I., Wong, J., Pettenella, D. *et al*. 2020. Non-wood forest products in Europe – A quantitative overview. *Forest Policy and Economics*, 116: 102175. doi: 10.1016/j.forpol.2020.102175

Low, M.C., Schmitz, N., Boeschoten, L.E., Cabezas, J.A., Cramm, M., Haag, V., Koch, G. *et al*. 2023. Tracing the world's timber: the status of scientific verification technologies for species and origin identification. *IAWA Journal*, 44(1): 63–84. doi: 10.1163/22941932-bja10097

Lowe, A. 2005. Population genetics of neotropical trees focus issue. *Heredity*, 95(4): 243–245. doi: 10.1038/sj.hdy.6800755

Lowe, A. J., Breed, M. F., Caron, H., Colpaert, N., Dick, C., Finegan, B. *et al.* 2018. Standardized genetic diversity-life history correlates for improved genetic resource management of Neotropical trees. *Diversity and Distributions*, 24(6): 730–741. doi: 10.1111/ddi.12716

Lstibůrek, M., Schueler, S., El-Kassaby, Y.A., Hodge, G.R., Stejskal, J., Korecký, J., Škorpík, P. ***et al.*** 2020. *In situ* genetic evaluation of European larch across climatic regions using marker-based pedigree reconstruction. *Frontiers in Genetics*, 11**,** Article 28. doi: 10.3389/fgene.2020.00028

Lu, M., Loopstra, C.A. & Krutovsky, K.V. 2019. Detecting the genetic basis of local adaptation in loblolly pine (*Pinus taeda* L.) using whole exome-wide genotyping and an integrative landscape genomics analysis approach. *Ecology and Evolution*, 9(12): 6798-6809. doi: 10.1002/ece3.5225

Lu, T., Brandt, M., Tong, X., Hiernaux, P., Leroux, L., Ndao, B. & Fensholt, R. 2022. Mapping the abundance of multipurpose agroforestry *Faidherbia albida* trees in Senegal. *Remote Sensing*, 14: article 662. doi: 10.3390/rs14030662

Lucas, S. 2013. *Bamboo*. London, Reaktion Books.

Luchi, N., Oliveira Longa, C.M., Danti, R., Capretti, P. & Maresi, G. 2014. *Diplodia* sapinea: the main fungal species involved in the colonization of pine shoots in Italy. *Forest Pathology*, 44(5): 372–381. doi: 10.1111/efp.12109

Lyam, P. T., Duque-Lazo, J., Hauenschild, F., Schnitzler, J., Muellner-Riehl, A. N., Greve, M. *et al.* 2022. Climate change will disproportionally affect the most genetically diverse lineages of a widespread African tree species. *Scientific Reports*, 12: 7035. doi: 10.1038/s41598-022-11182-z

Ma, P.-F., Vorontsova, M.S., Nanjarisoa, O.P., Razanatsoa, J., Guo, Z.-H., Haevermans, T. & Li, D.-Z. 2017. Negative correlation between rates of molecular evolution and flowering cycles in temperate woody bamboos revealed by plastid phylogenomics. *BMC Plant Biology*, 17: 260. doi: 10.1186/s12870-017-1199-8

Mackenzie, B.D.E., Clarke, S.W., Zimmer, H.C., Liew, E.C., Phelan, M.T., Offord, C.A. *et al.* 2022. Ecology and conservation of a living fossil: Australia's Wollemi pine (*Wollemia nobilis*). *In* D.A. DellaSala & M.I. Goldstein, eds. *Imperiled: The Encyclopedia of Conservation*, pp. 884–894. Amsterdam, Elsevier.

Mahony, C.R., MacLachlan, I.R., Lind, B.M., Yoder, J.B., Wang, T. & Aitken, S.N. 2020. Evaluating genomic data for management of local adaptation in a changing climate: A lodgepole pine case study. *Evolutionary Applications*, 13(1): 116-131. doi: 10.1111/eva.12871

Marchelli, P., Thomas, E., Azpilicueta, M.M., Van Zonneveld, M. & Gallo, L. 2017. Integrating genetics and suitability modelling to bolster climate change adaptation planning in Patagonian Nothofagus forests. *Tree Genetics & Genomes*, 13(6): 1–14. doi: 10.1007/s11295-017-1201-5

Marcó, M. A., Gomez, C., Vega, C. D., Luna, C. M., Chávez Díaz, L., Acuña, C. V. *et al.* eds. 2016. *Domesticación y mejoramiento de especies forestales*. Ministerio de Agroindustria, UCAR. Buenos Aires, 422 pp. (also available at https://forestoindustria.magyp.gob.ar/archivos/biblioteca-forestal/domesticacion-y-mejoramiento-de-especies-forestales.pdf).

Marjokorpi, A. & Ruokolainen, K. 2003. The role of traditional forest gardens in the conservation of tree species in West Kalimantan, Indonesia. *Biodiversity and Conservation*, 12: 799–822. doi: 10.1023/A:1022487631270

Marjoram, P., Zubair, A. & Nuzhdin, S.V. 2014. Post-GWAS: Where next? More samples, more SNPs or more biology? *Heredity*, 112:79–88. doi: 10.1038/hdy.2013.52

Mark, J., Newton, A.C., Oldfield, S. & Rivers, M. 2014. *The international timber trade: A working list of commercial timber tree species*. Botanic Gardens Conservation International. Richmond, UK.

Martin, M., Geiger, K., Singhakumara, B.M.P. & Ashton, M.S. 2019. Quantitatively characterizing the floristics and structure of a traditional homegarden in a village landscape, Sri Lanka. *Agroforestry Systems*, 93: 1439–1454. doi: 10.1007/s10457-018-0254-2

Martin, M., Morin, H. & Fenton, N.J. 2019. Secondary disturbances of low and moderate severity drive the dynamics of eastern Canadian boreal old-growth forests. *Annals of Forest Science*, 76: 108. doi: 10.1007/s13595-019-0891-2

Matricardi, E.A.T., Skole, D.L., Costa, O.B., Pedlowski, M.A., Samek, J.H. & Miguel, E.P. 2020. Long-term forest degradation surpasses deforestation in the Brazilian Amazon. *Science*, 369(6509): 1378–1382. doi: 10.1126/science.abb3021

Mattana, E., Peguero, B., Di Sacco, A., Agramonte, W., Encarnación Castillo, W. R., Jiménez, F., Clase, T. *et al.* 2020. Assessing seed desiccation responses of native trees in the Caribbean. *New For*, 51: 705–721. doi: 10.1007/s11056-019-09753-6

Mattera, M.G., Pastorino, M.J., Lantschner, M.V., Marchelli, P. & Soliani, C. 2020. Genetic diversity and population structure in *Nothofagus pumilio*, a foundation species of Patagonian forests: defining priority conservation areas and management. *Scientific Reports*, 10: 19231. doi: 10.1038/s41598-020-76096-0

Mattioni, C., Martin, M.A., Chiocchini, F., Cherubini, M., Gaudet, M., Pollegioni, P. *et al.* 2017. Landscape genetics structure of European sweet chestnut (*Castanea sativa* Mill): indications for conservation priorities. *Tree Genetics & Genomes*, 13(2): 1-14. doi: 10.1007/s11295-017-1123-2

Mátyás, C. 2010. Forecasts needed for retreating forests. *Nature*, 464(7293): 1271. doi: 10.1038/4641271a

Mátyás, C., Berki, I., Czúcz, B., Gálos, B., Móricz, N. &

Rasztovits, E. 2010. Future of beech in Southeast Europe from the perspective of evolutionary ecology. *Acta Silvatica et Lignaria Hungarica,* 6: 91–110. http://publicatio.uni-sopron.hu/110/1/08_matyas_et_al_p.pdf

Mátyás, C. 2021. Adaptive pattern of phenotypic plasticity and inherent growth reveal the potential for assisted transfer in sessile oak (*Quercus petraea* L.). *Forest Ecology and Management* 482: 1–9. doi: 10.1016/j.foreco.2020.118832

McCall, M.A. 1939. Forest Seed Policy of U.S. Department of Agriculture. Briefer Articles and Notes. pp 820–821.

McKeand, S.E. Payn, K.G. Heine, A.J. & Abt, R.C. 2021. Economic significance of continued improvement of loblolly pine genetics and its efficient deployment to landowners in the southern United States. Journal of Forestry, 119(1): 62–72. doi: 10.1093/jofore/fvaa044

McKinnell, F.H. 2002. Status and Trends in Indicators of Forest Genetic Diversity. Forest Genetic Resources Working Papers, Working Paper FGR/38E. Forest Resources Development Service, Forest Resources Division. FAO, Rome. https://www.fao.org/3/AC786E/ac786e00.htm

McLachlan, J., Hellmann, J.J. & Schwartz, M.W. 2007. A framework for debate of assisted migration in an era of climate change. *Conservation Biology*, 21(2): 297–302. https://www.jstor.org/stable/4620812

McLaughlin, B., Fogg, A., Ennis, K.K., Halstrom, G., Herrera, A. & Quadri, P. 2022. Climate change-adaptive participatory field gene banking for a California endemic oak. *Restoration Ecology*, 30(5): e13573. doi: 10.1111/rec.13573

McMullin, S., Njogu, K., Wekesa, B., Gachuiri, A., Ngethe, E., Stadlmayr, B. *et at.* 2019. Developing fruit tree portfolios that link agriculture more effectively with nutrition and health: A new approach for providing year-round micronutrients to smallholder farmers. *Food Security*, 11: 1355–1372. doi: 10.1007/s12571-019-00970-7

McMullin, S., Stadlmayr, B., Mausch, K., Revoredo-Giha, C., Burnett, F., Guarino, L. *et al.* 2021. Determining appropriate interventions to mainstream nutritious orphan crops into African food systems. *Global Food Security*, 28: article 100465. doi: 10.1016/j.gfs.2020.100465

McNeely, J.A. 1994. Lessons from the past: forests and biodiversity. *Biodiversity and Conservation*, 3: 3–20. doi: 10.1007/BF00115329

MEA (Millennium Ecosystem Assessment). 2005. *Ecosystems and Human Well-being: Synthesis*. Island Press, Washington, DC.

Méndez, V., Gliessman, S.R. & Gilbert, G.S. 2007. Tree biodiversity in farmer cooperatives of a shade coffee landscape in western El Salvador. *Agriculture, Ecosystems & Environment*, 119: 145–159. doi: 10.1016/J.AGEE.2006.07.004

Menon, M., Bagley, J.C., Page, G.F., Whipple, A.V., Schoettle, A.W., Still, C.J. *et al*. 2021. Adaptive evolution in a conifer hybrid zone is driven by a mosaic of recently introgressed and background genetic variants. *Communications Biology*, 4(1): 1–14. doi: 10.1038/s42003-020-01632-7

Metzger, M.J., Bunce, R.G., Jongman, R.H., Sayre, R., Trabucco, A. & Zomer, R. 2013. A high-resolution bioclimate map of the world: a unifying framework for global biodiversity research and monitoring. *Global Ecology and Biogeography*, 22(5): 630–638. doi: 10.1111/geb.12022

Milesi, P., Kastally, C., Dauphin, B., Cervantes, S., Bagnoli, F., Budde, K. B., Cavers, S. *et al.* 2024. Resilience of genetic diversity in forest trees over the Quaternary. *Nature Communications*, 15: 8538. doi: 10.1101/2023.01.05.522822

Millar, C.I. & Libby, W.J. 1991. Strategies for conserving clinal, ecotipic, and disjunct population diversity in widespread species. In: D.A. Falk & K.E. Holsinger, eds. *Genetics and conservation of rare plants*, pp 149–170. New York, USA, Oxford University Press. doi: 10.1093/oso/9780195064292.001.0001

Monthe, F.K., Migliore, J., Duminil, J., Bouka, G., Demenou, B.B., Doumenge, C. *et al*. 2019. Phylogenetic relationships in two African Cedreloideae tree genera (Meliaceae) reveal multiple rain/dry forest transitions. *Perspectives in Plant Ecology, Evolution and Systematics*, 37: 1-10. doi: 10.1016/j.ppees.2019.01.002

Montréal Process. 2015. Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests. Fifth Edition, September 2015. https://montreal-process.org/documents/publications/techreports/MontrealProcessSeptember2015.pdf

Moritz, C. 1994. Defining 'evolutionarily significant units' for conservation. *Trends in Ecology & Evolution*, 9(10): 373–375. doi: 10.1016/0169-5347(94)90057-4

Mucina, L. 2019. Biome: evolution of a crucial ecological and biogeographical concept. *New Phytologist,* 222(1): 97–114. doi: 10.1111/nph.15609

Mudio, D.M., Gogoi, B. & Borah, G. 2023. An assessment for in vitro propagation and genetic stability of *Phoebe goalparensis* Hutchinson, an endemic valuable timber tree of north east India. [Journal details not provided]. doi: 10.1186/s43141-023-00487-9

Mudoi, K.D., Saikia, S.P., Goswami, A., Gogoi, A., Bora, D. & Borthakur, M. 2013. Micropropagation of important bamboos: A review. *African Journal of Biotechnology*, 12: 2770–2785. doi: 10.5897/AJB12.2122

Muir, G.F., Sorrenti, S., Vantomme, P., Vidale, E. & Masiero, M. 2020. Into the Wild: Disentangling Non-Wood Terms and Definitions for Improved Forest Statistics. *International Forestry Review*, 22(1): 101–119. doi: 10.1505/146554820828671553

Murphy, P. G. & Lugo, A. E. 1986. Ecology of Tropical Dry Forest. *Annual Review of Ecology and Systematics*, 17: 67–88. doi: 10.1146/annurev.ecolsys.17.1.67

Muscarella, R., Emilio, T., Phillips, O. L., Lewis, S. L., Slik, F., Baker, W. J. *et al.* 2020. The global abundance of tree palms. *Global Ecology and Biogeography*, 29(9): 1495–1514. doi: 10.1111/geb.13123

Myburg, A.A., Grattapaglia, D., Tuskan, G.A., Hellsten, U., Hayes, R.D., Grimwood, J. *et al.* 2014. The genome of *Eucalyptus grandis*. *Nature*, 510: 356–362 doi: 10.1-38/nature13308

NAFC (North American Forest Commission). 2023. *NAFC home page*. [Cited 21 September 2024]. https://northamericanforestcommission.com/

Naidoo, S., Slippers, B., Plett, J.M., Coles, D.& Oates, C.N. 2019. The road to resistance in forest trees. *Frontiers in plant science*, 10: 273. doi: 10.3389/fpls.2019.00273

Nair, P.K.R., Kumar, B.M. & Nair, V.D. 2022. An introduction to agroforestry. four decades of scientific developments. Cham, Switzerland, Springer Nature. doi: 10.1007/978-3-030-75358-0

Namkoong, G., Barnes, R.D. & Burley, J. 1980. *A philosophy of breeding strategy for tropical forest trees*. Tropical Forestry Papers No. 16. Oxford, UK, Commonwealth Forestry Institute, University of Oxford.

National Academies of Sciences, Engineering, and Medicine. 2019. *Forest health and biotechnology: Possibilities and considerations*. Washington, DC, National Academies Press.

Natural Resources Canada. 2022. *The state of Canada's forests. Annual Report 2022*. Ottawa. NRCAN_SofForest_Annual_2023_EN_accessible-vf(1)

Nature Biotechnology News. 2015. Brazil approves transgenic eucalyptus. *Nature Biotechnology*, 33: 577. doi: 10.1038/nbt0615-577c

Neale, D.B. & Wheeler, N.C. 2019. The conifers. In: D.B. Neale & N.C. Wheeler, eds. *The conifers: genomes, variation and evolution*, pp. 1–21. Cham, Switzerland, Springer.

Nehoshtan, Y., Carmon, E., Yaniv, O., Ayal, S., & Rotem, O. 2021. Robust seed germination prediction using deep learning and RGB image data. *Scientific reports*, *11*(1): 22030. doi: 10.1038/s41598-021-01712-6

Nelson, C.D. 2023. Tree breeding, a necessary complement to genetic engineering. *New Forests*, 54(4): 721–738. doi: 10.1007/s11056-022-09931-z

Nelson, C.R., Hallett, J.G., Romero Montoya, A.E., Andrade, A., Besacier, C., Boerger, V., Bouazza,

K. *et al*. 2024. *Standards of practice to guide ecosystem restoration – A contribution to the United Nations Decade on Ecosystem Restoration 2021-2030*. Rome, FAO, Washington, DC, SER & Gland, Switzerland, IUCN CEM. doi: 10.4060/cc9106en

Neophytou, C., Heer, K., Milesi, P., Peter, M., Pyhäjärvi, T., Westergren, M. *et al*. 2022. Genomics and adaptation in forest ecosystems. *Tree Genetics & Genomes*, 18(2): 1–7. doi: 10.1007/s11295-022-01542-1

Newton, A. C., Allnutt, T. R., Gillies, A. C. M., Lowe, A. J. & Ennos, R. A. 1999. Molecular phylogeography, intraspecific variation and the conservation of tree species. *Trends in Ecology & Evolution*, 14: 140–145. doi: 10.1016/s0169-5347(98)01555-9

Newton, P., Castle, S.E., Kinzer, A.T., Miller, D.C., Oldekop, J.A., Linhares-Juvenal, T., Pina, L. *et al.* 2022. *The number of forest- and tree-proximate people – A new methodology and global estimates*. Forestry Working Paper No. 34. Rome, FAO. doi: 10.4060/cc2544en

Nishiguchi, M., Futamura, N., Endo, M., Mikami, M., Toki, S., Katahata, S.I., Yasunori, O. *et al.* 2023. CRISPR/Cas9-mediated disruption of *CjACOS5* confers no-pollen formation on Sugi trees (*Cryptomeria japonica* D. Don). *Scientific Reports*, 13: 11779. doi: 10.1038/s41598-023-38339-8

Nock, C.J., Baten, A., Mauleon, R., Langdon, K.S., Topp, B., Hardner, C. *et al*. 2020. Chromosome-scale assembly and annotation of the macadamia genome (*Macadamia integrifolia* HAES 741) G3 *Genes|Genomes|Genetics*, 10: 3497–3504. doi: 10.1534/g3.120.401326

Nunes, S., Gastauer, M., Cavalcante, R. B. L., Ramos, S. J., Caldeira, C. F., Jr., Silva, D., Rodrigues, R. R. *et al.* 2020. Challenges and opportunities for large-scale reforestation in the eastern Amazon using native species. *For Ecol Manage*, 466: 118120. doi: 10.1016/j.foreco.2020.118120

O'Brien, C., Hiti-Bandaralage, J., Folgado, R., Hayward, A., Lahmeyer, S., Folsom, J., Mitter, N. 2021. Cryopreservation of woody crops: the avocado case. *Plants*, 10: 934. doi: 10.3390/plants10050934

O'Donnell, K. & Sharrock, S. 2017. The contribution of botanic gardens to *ex situ* conservation through seed banking. *Plant Divers*, 39: 373–378. doi: 10.1016/j.pld.2017.11.005

O'kting'ati, A., Maghembe, J.A., Fernandes, E.C.M. & Weaver, G.H. 1984. Plant species in the Kilimanjaro agroforestry system. *Agroforestry Systems*, 2: 177–186. doi: 10.1007/BF00147032

O'Neill, G., Wang, T., Ukrainetz, N., Charleson, L., McAuley, L., Yanchuk, A. & Zedel, S. 2017. *A proposed climate-based seed transfer system for British Columbia*. Technical Report-Ministry of Forests, Lands and Natural Resource Operations, British Columbia (099). www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr099.htm

O'Neill, G.A & Gómez-Pineda, E. 2021. Local *was* best: sourcing tree seed for future climates. *Canadian Journal of Forest Research*, 51(10): 1432–1439. doi: 10.1139/cjfr-2020-0408

Obroucheva, N., Sinkevich, I. & Lityagina, S. 2016. Physiological aspects of seed recalcitrance: a case study on the tree *Aesculus hippocastanum*. *Tree Physiol*, 36: 1127–1150. doi: 10.1093/treephys/tpw037

OECD (Organisation for Economic Co-operation and Development). 2018. *Forest Seed and Plant Scheme Strategic Plan.* [Cited 18 September 2023]. https://www.oecd.org/agriculture/forest/documents/strategic-plan-for-the-oecd-forest-seed-and-plant-scheme.pdf

OECD. 2022. *Forest Seed and Plant Scheme - Planting sustainable forests for the future*. https://www.oecd.org/agriculture/forest/documents/2022%20oecd-forests-scheme-brochure.pdf

OECD. 2023. *Rules and Regulations: OECD Forest Seed and Plant Scheme*. Paris.

Ohrnberger, D. 1999. *The Bamboos of the world: Annotated nomenclature and literature of the species and the higher and lower taxa*. Amsterdam and New York, Elsevier Science.

Oldfield, S., Lusty, C. & MacKinven, A. 1998. *The world list of threatened trees*. Cambridge, UK, World Conservation Press.

Oliver, C.D. & Larson, B.A. 1996. Forest stand dynamics. Update Edition. *FES Other Publications*, 1. https://elischolar.library.yale.edu/fes_pubs/1.

Olsson, S., Dauphin, B., Jorge, V., Grivet, D., Farsakoglou, A. M., Climent, J., Alizoti, P. *et al.* 2023. Diversity and enrichment of breeding material for resilience in European forests. *For Ecol Manage*, 530: 120748. doi: 10.1016/j.foreco.2022.120748

Ortiz-Bibian, M.A., Blanco-García, A., Lindig-Cisneros, R.A., Gómez-Romero, M. Castellanos-Acuña, D., Herrerías-Diego, Y., Sánchez-Vargas, N.M., & Sáenz-Romero, C. 2017. Genetic variation in *Abies religiosa* for quantitative traits and delineation of elevational and climatic zoning for maintaining Monarch Butterfly overwintering sites in Mexico, considering climatic change. *Silvae Genetica* 66(1):14–23. doi: 10.1515/sg-2017-0003

Ottewell, K.M., Bickerton, D.C., Byrne, M., Lowe, A.J. 2016. Bridging the gap: a genetic assessment framework for population-level threatened plant conservation prioritization and decision-making. *Diversity and Distributions*, 22: 174–188. doi: 10.1111/ddi.12387

Ousmael, K.M., Cappa, E.P., Hansen, J.K., Hendre, P. & Hansen, O.K. 2024. Genomic evaluation for breeding and genetic management in *Cordia africana*, a multipurpose tropical tree species. *BMC Genomics*, 25: 9. doi: 10.1186/s12864-023-09907-z

Pais, A.L., Whetten, R.W. & Xiang, Q. (Jenny). 2017. Ecological genomics of local adaptation in *Cornus florida* L. by genotyping by sequencing. *Ecology and Evolution*, *7*(1): 441–465. doi: 10.1002/ece3.2623

Palmberg-Lerche, C. 2001. *International action in the management of forest genetic resources: status and challenges*. Forest Resources Development Service Working Paper FGR/1. Rome, FAO.

Palmberg-Lerche, C. 2007. *Technical review of status and trends of the world's forest genetic resources*. Background Study Paper No. 36. Commission on Genetic Resources for Food and Agriculture. Rome, FAO. http://www.fao.org/3/a-k0104e.pdf

Palmer, M.A. & Stewart, G.A. 2020. Ecosystem restoration is risky…but we can change that. *One Earth*, 3: 661–664. doi: 10.1016/j.oneear.2020.11.019

Pandey, M. & Rajora, O.P. 2012. Genetic diversity and differentiation of core vs. peripheral populations of eastern white cedar, *Thuja occidentalis* (Cupressaceae). *American Journal of Botany*, 99(4): 690–699. doi: 10.3732/ajb.1100116

Parent, G.J., Méndez-Espinoza, C., Giguère, I., Mageroy, M.H., Charest, M., Bauce, É., Bohlmann, J. & MacKay, J.J. 2020. Hydroxyacetophenone defenses in white spruce against spruce budworm. *Evolutionary Applications*, 13(1): 62–75. doi: 10.1111/eva.12885

Pastorino, M.J. & Marchelli, P. 2021. *Low intensity breeding of native forest trees in Argentina: Genetic basis for their domestication and conservation*. Cham, Switzerland, Springer. doi: 10.1007/978-3-030-56462-9

Pastorino, M.J., Aparicio, A.G. & Azpilicueta, M.M. 2015. Regiones de procedencia del ciprés de la Cordillera y bases conceptuales para el manejo de sus recursos genéticos en Argentina. Buenos Aires, Instituto Nacional de Tecnología (INTA). https://ri.conicet.gov.ar/handle/11336/192348

Paudyal, K., Li, Y., Long, T., Adhikari, S., Lama, S. & Bhatta, K.S. 2022. Ecosystem services from bamboo forests: Key findings, lessons learnt and call for actions from global synthesis. INBAR Working Paper. Beijing, International Center for Bamboo and Rattan.

Pausas, J.G. & Bond, W.J. 2020. Alternative Biome States in Terrestrial Ecosystems. *Trends in Plant Science* 25(3): 250–263. doi: 10.1016/j.tplants.2019.11.003

Paysen, T. E., Ansley, R., Brown, J. K., Gottfried, G. J., Haase, S. M., Harrington, M., Narog, M. *et al.* 2000. Fire in western shrubland, woodland, and grassland ecosystems. *Wildland Fire in Ecosystems: Effects of Fire on Flora*, 2: 121–159.

Pearcy, R. W. & Robichaux, R. H. 1985. Tropical and subtropical forests. *In* B.F. Chabot & H.A. Mooney, eds. *Physiological Ecology of North American Plant Communities*. Dordrecht, Springer.

Pedercini, F., Dawson, I.K., Lillesø, J.-P.B., Moestrup, S., Nørgaard, C.T., Abiyu, A., Eshete, G. *et al.* 2022. Cost benefit analysis for *Grevillea robusta* in Ethiopia: linking establishment of a breeding seedling orchard to the economic returns of quality plantings. CIFOR-ICRAF Working Paper No. 6. Bogor, Indonesia & Nairobi, Kenya: CIFOR and World Agroforestry. doi: 10.17528/cifor-icraf/008579

Pedlar, J.H., McKenney, D.W., Aubin, I., Beardmore, T., Beaulieu, J., Iverson, L., O'Neill, G.A. *et al*. 2012. Placing forestry in the assisted migration debate. *BioScience*, 62(9): 835–842. doi: 10.1525/bio.2012.62.9.10

Pedlar, J.H., McKenney, D.W. & Lu, P. 2021.Critical seed transfer distances for selected tree species in eastern North America. *Journal of Ecology* 109: 2271–2283. doi: 10.1111/1365-2745.13605

Pedlar, J.H., McKenney, D.W., Aubin, I., Beardmore, T., Beaulieu, J., Iverson, L., O'Neill, G.A. *et al*. 2012. Placing forestry in the assisted migration debate. *BioScience*, 62(9): 835–842. doi: 10.1525/bio.2012.62.9.10

Pence, V.C., Meyer, A., Linsky, J., Gratzfeld, J., Pritchard, H.W., Westwood, M. & Bruns, E.B. 2022. Defining exceptional species—a conceptual framework to expand and advance *ex situ* conservation of plant diversity beyond conventional seed banking. *Biol Conserv*, 266: 109440. doi: 10.1016/j.biocon.2021.109440

Pennington, P. T., Cronk, Q. C. B., Richardson, J. A., Crisp, M., Cook, L. & Steane, D. 2004. Radiation of the Australian flora: what can comparisons of molecular phylogenies across multiple taxa tell us about the evolution of diversity in present–day communities? *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 359(1450): 1551–1571. doi: 10.1098/rstb.2004.1528

Peñuelas, J., Oyaga, R., Boada, M. & Jump, A.S. 2007. Migration, invasion and decline: changes in recruitment and forest structure in a warming-linked shift of European beech forest in Catalonia (NE Spain). *Ecography*, 30(6): 830–838. doi: 10.1111/j.2007.0906-7590.05247.x

Peri, P.L., Rosas, Y.M., Lopez, D.R., Lencinas, M.V., Cavallero, L. & Martínez Pastur, G.J. 2022. Conceptual framework to define management strategies for silvopastoral systems in native forests. *Ecología Austral* 32:749-766. doi: 10.25260/ea.22.32.2.1.1872

Peterson St-Laurent, G.P., Hagerman, S., Findlater, K.M. & Kozak, R. 2019. Public trust and knowledge in the context of emerging climate-adaptive forestry policies. *Journal of environmental management*, 242: 474–486. doi: 10.1016/j.jenvman.2019.04.065

Petit, R.J., El Mousadik, A. & Pons, O. 1998. Identifying populations for conservation on the basis of genetic markers. *Conservation Biology*, 12(4): 844–855. doi: 10.1111/j.1523-1739.1998.96489.x

Petit, R.J. & Hampe, A. 2006. Some evolutionary consequences of being a tree. *Annual Review of Ecology and Evolutionary Systems*, 37: 187–214.

Petit, R.J., Aguinagalde, I., de Beaulieu, J.-L., Bittkau, C., Brewer, S., Cheddadi, R., Ennos, R. *et al*. 2003. Glacial refugia: Hotspots but not melting pots of genetic diversity. *Science*, 300: 1563–1565. doi: 10.1126/science.1083264

Pijut, P.M., Beasley, R.R., Lawson, S.S., Palla, K.J., Stevens, M.E. & Wang, Y. 2012. *In vitro* propagation of tropical hardwood tree species—a review. *Propag Ornam Plants*, 12: 25–51.

Piñeiro, R., Dauby, G., Kaymak, E. & Hardy, O.J. 2017. Pleistocene population expansions of shade-tolerant trees indicate fragmentation of the African rainforest during the Ice Ages. *Proceedings of the Royal Society B: Biological Sciences*, 284(1866): p.20171800. doi: 10.1098/rspb.2017.1800

Piñeiro, R., Hardy, O.J., Tovar, C., Gopalakrishnan, S., Garrett Vieira, F. & Gilbert, M.T.P. 2021. Contrasting genetic signal of recolonization after rainforest fragmentation in African trees with different dispersal abilities. *Proceedings of the National Academy of Sciences*, 118(27):

e2013979118. doi: 10.1073/pnas.2013979118

Piotti, A., Leonarduzzi, C., Postolache, D., Bagnoli, F., Spanu, I., Brousseau, L. *et al*. 2017. Unexpected scenarios from Mediterranean refugial areas: disentangling complex demographic dynamics along the Apennine distribution of silver fir. *Journal of Biogeography*, 44(7): 1547–1558. doi: 10.1111/jbi.13011

Plomion, C., Aury, J.M., Amselem, J., Alaeitabar, T., Barbe, V., Belser, C., Bergès, H. *et al.* 2016a. Decoding the oak genome: public release of sequence data, assembly, annotation and publication strategies. *Molecular ecology resources*, 16(1): 254–265. doi: 10.1111/1755-0998.12425

Plomion, C., Bastien, C., Bogeat-Triboulot, M.B., Bouffier, L., Déjardin, A., Duplessis, S. *et al*. 2016b. Forest tree genomics: 10 achievements from the past 10 years and future prospects. *Annals of Forest Science*, 73(1): 77–103. doi: 10.1007/s13595-015-0488-3

Poland, T.M., Patel-Weynand, T., Finch, D., Miniat, C.F., Hayes, D.C. & Lopez, V.M. eds. 2021. *Invasive species in forests and rangelands of the United States: a comprehensive science synthesis for the United States forest sector*. Cham, Switzerland, Springer. doi: 10.1007/978-3-030-45367-1

Postolache, D., Curtu, A.L., Şofletea, N. & Popescu, F. 2019. Conservation and management of Romanian forest genetic resources in the context of climate change. In: M. Šijačić-Nikolić, J. Milovanović & M. Nonić, eds., 2019. *Forests of southeast Europe under a changing climate: conservation of genetic resources,* pp. 389–399. Berlin/Heidelberg, Germany, Springer International Publishing*.*

Potter, K.M., Crane, B.S. & Hargrove, W.W. 2017. A United States national prioritization framework for tree species vulnerability to climate change. *New Forests*, 48(2): 275–300. doi: 10.1007/s11056-017-9569-5

Potter, K.M., Jetton, R.M., Bower, A., Jacobs, D.F., Man, G., Hipkins, V.D. *et al*. 2017. Banking on the future: progress, challenges and opportunities for the genetic conservation of forest trees. *New Forests*, 48(2): 153–180. doi: 10.1007/s11056-017-9582-8

Powell, W.A., Newhouse, A.E. & Coffey, V. 2019. Developing blight-tolerant American chestnut trees. *Cold Spring Harbor Perspectives in Biology*, 11(7): a034587. doi: 10.1101/cshperspect.a034587

POWO. 2021. *Plants of the world online*. Cited 1 November 2021. http://www.plantsoftheworldonline.org

Pritchard, H. W., Moat, J. F., Ferraz, J. B., Marks, T. R., Camargo, J. L. C., Nadarajan, J., & Ferraz, I. D. 2014. Innovative approaches to the preservation of forest trees. *For Ecol Manage*, 333: 88–98. doi: 10.1016/j.foreco.2014.08.012

Probert, R.J., Daws, M.I. & Hay, F.R. 2009. Ecological correlates of ex situ seed longevity: a comparative study on 195 species. *Ann Bot*, 104: 57–69. doi: 10.1093/aob/mcp082

Pureswaran, D.S., Roques, A. & Battisti, A. 2018. Forest insects and climate change. *Current Forestry Reports*, 4: 35–50. doi:10.1007/s40725-018-0075-6

Putz, F.E. 1990. Growth habits and trellis requirements of climbing palms (*Calamus*-spp) in north-eastern Queensland. *Australian Journal of Botany*, 38: 603–608. doi: 10.1071/bt9900603

Pyhäjärvi, T., Kujala, S.T. & Savolainen, O. 2020. 275 years of forestry meets genomics in *Pinus sylvestris*. *Evolutionary Applications*, 13(1): 11–30. doi: 10.1111/eva.12809

Quiñones-Pérez, C.Z., González-Elizondo, M.D.S. & Wehenkel, C. 2017. Ruling out genetic erosion in *Picea chihuahuana* Martínez. *New Forests*, 48(2): 201–215. doi: 10.1007/s11056-017-9581-9

Rajora, O.P., Eckert, A.J. & Zinck, J.W. 2016. Single-locus versus multilocus patterns of local adaptation to climate in eastern white pine (*Pinus strobus*, Pinaceae). *PLoS ONE*, 11(7): e0158691. doi: 10.1371/journal.pone.0158691

Rajora, O.P. & Zinck, J.W. 2021. Genetic diversity, structure and effective population size of old-growth vs. second-growth populations of keystone and long-lived conifer, Eastern

White Pine (*Pinus strobus*): Conservation value and climate adaptation potential. *Frontiers in Genetics*, 12. Doi: 10.3389/fgene.2021.650299

Ramírez-Valiente, J.A., Santos del Blanco, L., Alía, R., Robledo-Arnuncio, J.J. & Climent, J. 2022. Adaptation of Mediterranean forest species to climate: Lessons from common garden experiments. *Journal of Ecology*, 110(5): 1022–1042. doi: 10.1111/1365-2745.13730

Rasche, L., Fahse, L. & Bugmann, H. 2013. Key factors affecting the future provision of tree-based forest ecosystem goods and services. *Climatic Change*, 118(3): 579–593. doi: 10.1007/s10584-012-0664-5

Rasolofoson, R.A., Hanauer, M.M., Pappinen, A., Fisher, B. & Ricketts, T.H. 2018. Impacts of forests on children's diet in rural areas across 27 developing countries. *Science Advances*, 4(8). doi: 10.1126/sciadv.aat2853

Ratnam, W., Rajora, O.M., Finkeldey, R. Aravanopoulos, F., Bouvet, J.-M., Vaillancourt, R.E., Kanashiro, M. *et al.* 2014. Genetic effects of forest management practices: Global synthesis and perspectives. *Forest Ecology and Management*, 333: 52–65. doi: 10.1016/j.foreco.2014.06.008

Ray, D., Berlin, M., Alia, R., Sanchez, L., Hynynen, J., González-Martinez, S. & Bastien, C. 2022. Transformative changes in tree breeding for resilient forest restoration. *Frontiers in Forests and Global Change*, 5: 1005761. doi: 10.3389/ffgc.2022.1005761

Rayner, R., Buck, A. & Katila, P. eds. 2010. *Embracing complexity: Meeting the challenges of international forest governance. A global assessment report*. Prepared by the Global Forest Expert Panel on the International Forest Regime. IUFRO World Series Vol. 28. Vienna.

RBG (Royal Botanic Gardens). 2022. *Kew Foundation Review of the year 2021-22, kew.org*. [Cited 25 September 2024]. https://www.kew.org/sites/default/files/2022-10/14537 Review of the Year 2021-22_A4_ISD_AC.pdf

RBG. 2024. *Plants of the World Online*. https://powo.science.kew.org/ [Cited 23 January 2024].

Reed, B.M. 2020. *In vitro* conservation of temperate tree fruit and nut crops. *Plant Conserv Biotechnol*, pp. 165–180. doi: 10.1201/9781482273038-18

Reed, D.H. & Frankham, R. 2003. Correlation between fitness and genetic diversity. *Conservation Biology*, 17(1): 230–237. doi: 10.1046/j.1523-1739.2003.01236.x

Reed, J., van Vianen, J., Foli, S., Clendenning, J., Yang, K., MacDonald, M., Petrokofsky, G. *et al*. 2017. Trees for life: the ecosystem service contribution of trees to food production and livelihoods in the tropics. *Forest Policy and Economics*, 84: 62–71. doi: 10.1016/j.forpol.2017.01.012

Rehfeldt, G.E. 1988. Ecological genetics of *Pinus contorta* from the Rocky Mountains (USA): a synthesis. *Silvae Genetica*, 37(3–4): 131–135.

Rehfeldt, G.E., Ying, C.C., Spittlehouse, D.L. & Hamilton, D.A., Jr. 1999. Genetic responses to climate in *Pinus contorta*: Niche breadth, climate change, and reforestation. *Ecological Monographs*, 69(3): 375–407. doi: 10.1890/0012-9615(1999)069[0375:GRTCIP]2.0.CO;2

Rehfeldt, G.E., Tchebakova, N.M., Parfenova, Y.I., Wykoff, W.R., Kuzmina, N.A. & Milyutin, L.I. 2002. Intraspecific responses to climate in *Pinus sylvestris*. *Global Change Biology*, 8(9): 912–929. doi: 10.1046/j.1365-2486.2002.00516.x

Rehfeldt, G.E., Crookston, N.L., Sáenz-Romero, C. & Campbell, E.M. 2012. North American vegetation model for land-use planning in a changing climate: A solution to large classification problems. Ecological Applications, 22(1): 119–141. doi: 10.1890/11-0495.1

Rehfeldt, G.E., Leites, L.P., Joyce, D.G. & Weiskittel, A.R. 2018. Role of population genetics in guiding ecological responses to climate. *Global Change Biology*, 24(2): 858–868. doi: 10.1111/gcb.13883

Rehfeldt, G.E., Warwell, M.V. & Monserud, R.A. 2020. Species, climatypes, climate change, and forest health: a conversion of science to practice for Inland Northwest (USA). *Forests*, 11(12): 1237. doi:10.3390/f11121237

Rekola, M., Nevgi, A. & Sandström, N. 2021. *Regional Assessment of Forest Education in Europe*. Rome, FAO. https://www.fao.org/3/cb6736en/cb6736en.pdf

Rekola, M. & Sharik, T.L. 2022. *Global assessment of forest education – Creation of a Global Forest Education Platform and Launch of a Joint Initiative under the Aegis of the Collaborative Partnership on Forests (FAO-ITTO-IUFRO project GCP /GLO/044/GER).* Forestry Working Paper No. 32. Rome, FAO. doi:10.4060/cc2196en

Rellstab, C., Dauphin, B. & Exposito-Alonso, M. 2021. Prospects and limitations of genomic offset in conservation management. *Evolutionary Applications*, 14(5): 1202-1212. doi: 10.1111/eva.13205

Renn, S.C. & Siemens, D.H. 2010. Ecological genomics—changing perspectives on Darwin's basic concerns. *Molecular Ecology*, 19(15): 3025–3030. doi: 10.1111/j.1365-294x.2010.04743.x

Ribeiro, N.S., Snook, L.K., Nunes de Carvalho Vaz, I.V. & Alves, T. 2019. Gathering honey from wild and traditional hives in the Miombo woodlands of the Niassa National Reserve, Mozambique: What are the impacts on tree populations? *Global Ecology and Conservation*, 17: e00552. doi: 10.1016/j.gecco.2019.e00552

Rigal, C., Vaast, P. & Xu, J. 2018. Using farmers' local knowledge of tree provision of ecosystem services to strengthen the emergence of coffee-agroforestry landscapes in southwest China. *PLoS ONE*, 13: e0204046. doi: 10.1371/journal.pone.0204046

Rimlinger, A., Avana, M.L., Awono, A., Chakocha, A., Gakwavu, A., Lemoine, T. *et al*. 2021a. Trees and their seed networks: The social dynamics of urban fruit trees and implications for genetic diversity. *PLoS ONE*, 16(3): p.e0243017. doi : 10.1371/journal.pone.0243017

Rimlinger, A., Duminil, J., Lemoine, T., Avana, M.L., Chakocha, A., Gakwavu, A. *et al*. 2021b. Shifting perceptions, preferences and practices in the African fruit trade: the case of African plum (*Dacryodes edulis)* in different cultural and urbanization contexts in Cameroon. *Journal of Ethnobiology and Ethnomedicine*, 17(1): 1–17. doi: 10.1186/s13002-021-00488-3

Rivers, M., Beech, E., Bazos, I., Boguni- , F., Buira, A., Caković, D., Carapeto, A. *et al.* 2019. *European red list of trees*. Cambridge, UK and Brussels, International Union for Conservation of Nature and Natural Resources. doi: 10.2305/IUCN.CH.2019.ERL.1.en

Rivers, M., Newton, A.C., Oldfield, S. & Global Tree Assessment Contributors. 2022. Scientists' warning to humanity on tree extinctions. *Plants, People, Planet* 5(4): 466–482. doi: 10.1002/ppp3.10314

Roberts, D. R. & Hamann, A. 2015. Glacial refugia and modern genetic diversity of 22 western North American tree species. *Proceedings of the Royal Society B: Biological Sciences*, 282. doi: 10.1098/rspb.2014.2903

Roberts, P., Hunt, C., Arroyo-Kalin, M., Evans, D. & Boivin, N. 2017. The deep human prehistory of global tropical forests and its relevance for modern conservation. *Nature Plants*, 3: 17093. doi: 10.1038/nplants.2017.93

Rodríguez Fernández-Blanco, C., Burns, S.L. & Giessen, L. 2019. Mapping the fragmentation of the international forest regime complex: institutional elements, conflicts and synergies. *International Environmental Agreements: Politics, Law and Economics*, 19: 187–205. doi: 10.1007/s10784-019-09434-x

Rodriguez-Piñeros, S. 2021. *Regional Assessment of Forest Education in Latin America and the Caribbean*. Rome, FAO. https://www.fao.org/3/cb6737en/cb6737en.pdf

Rodríguez-Quilón, I., Santos-del-Blanco, L., Serra-Varela, M.J., Koskela, J., González-Martínez, S.C. & Alía, R. 2016. Capturing neutral and adaptive genetic diversity for conservation in a highly structured tree species. *Ecological Applications*, 26(7): 2254–2266. doi: 10.1002/eap.1361

Romero-Rodríguez, M.C., Jorrín-Novo, J.V. & Castillejo, M.A. 2019. Toward characterizing germination and early growth in the non-orthodox forest tree species *Quercus ilex* through complementary gel and gel-free proteomic analysis of embryo and seedlings. *J Proteomics*, 197: 60–70. doi: 10.1016/j.jprot.2018.11.003

Rosenstock, T.S., Wilkes, A., Jallo, C., Namoi, N., Bulusu, M., Suber, M., Mboi, D. *et al*. 2019. Making trees count: measurement and reporting of agroforestry in UNFCCC national communications of non-Annex I countries. *Agriculture, Ecosystems & Environment*, 284: article 106569. doi: 10.1016/j.agee.2019.106569

Rossetto, M., Wilson, P.D., Bragg, J., Cohen, J., Fahey, M., Yap, J.Y.S. & van der Merwe, M. 2020. Perceptions of similarity can mislead provenancing strategies—An example from five co-distributed acacia species. *Diversity*, 12(8): 306. doi: 10.3390/d12080306

Royal Botanical Gardens K. 2022. Seed Information Database (SID) [accessed 27 July 2022]. http://data.kew.org/sid/

RRI. 2018. *At a crossroads: Consequential trends in recognition of community-based forest tenure from 2002–2017*. Rights and Resources Initiative. doi: 10.53892/UCYL3747

Ruiz-Sanchez, E. 2015. Parametric and non-parametric species delimitation methods result in the recognition of two new Neotropical woody bamboo species. *Molecular Phylogenetics and Evolution*, 93: 261–273. http://dx.doi.org/10.1016/j.ympev.2015.08.004doi: 10.1016/j.ympev.2015.08.004

Ruiz-Sanchez, E., Tyrrell, C.D., Londoño, X., Oliveira, R.P. & Clark, L.G. 2021. Diversity, distribution, and classification of Neotropical woody bamboos (Poaceae: Bambusoideae) in the 21st Century. *Botanical Sciences*, 99(2): 198–228. https://dx.doi.org/10.17129/botsci.2722doi: 10.17129/botsci.2722

Ruiz-Talonia, L.F., Sánchez-Vargas, N.M., Bayuelo-Jiménez, J.S., Lara-Cabrera, S.I. & Sáenz-Romero, C. 2014. Altitudinal genetic variation among native *Pinus patula* provenances: performance in two locations, seed zone delineation and adaptation to climate change. *Silvae Genetica*, 63(4), 139–149. https://www.thuenen.de/media/institute/fg/PDF/Silvae_Genetica/2014/Vol._63_Heft_4/63_4_139.pdf

Rutherford, M. C., Mucina, L. & Powrie, L. 2006. Biomes and bioregions of Southern Africa. *In* L. Mucina & M.C. Rutherford, eds. *The vegetation of South Africa, Lesotho and Swaziland*, pp. 30–51. Pretoria, SANBI.

Saah, D., Johnson, G., Ashmall, B., Tondapu, G., Tenneson, K., Patterson, M., Poortinga, A. *et al*. 2019. Collect Earth: an online tool for systematic reference data collection in land cover and use applications. *Environmental Modelling & Software*, 118: 166–171. doi: 10.1016/j.envsoft.2019.05.004

Sabatini, F.M., Jiménez-Alfaro, B., Jandt, U., Chytrý, M., Field, R., Kessler, M. *et al.* 2022. Global patterns of vascular plant alpha diversity. Nature Communications, 13: 4683. doi: 10.1038/s41467-022-32063-z

Sabogal, C., Guariguata, M.R., Broadhead, J., Lescuyer, G., Savilaakso, S., Essoungou, N. & Sist, Pi. 2013. *Multiple-use forest management in the humid tropics: opportunities and challenges for sustainable forest management*. FAO Forestry Paper No. 173. Rome, FAO, and Bogor, Indonesia, Center for International Forestry Research. https://openknowledge.fao.org/handle/20.500.14283/i3378e

Sacande, M., Jøker, D., Dulloo, M.E. & Thomsen, K.A. eds. 2004. *Comparative storage biology of tropical tree seeds*. Rome, Bioversity International. ISBN: 978-92-9043-641-6

Sáenz-Romero, C., Guzmán-Reyna, R. & Rehfeldt, G.E. 2006. Altitudinal genetic variation among *Pinus oocarpa* populations in Michoacán, México; implications for seed zoning, conservation of forest genetic resources, tree breeding and global warming. *Forest Ecology and Management*, 229: 340–350. doi: 10.1016/j.foreco.2006.04.014

Sáenz-Romero, C. & Tapia-Olivares, B.L. 2008. Genetic variation in frost damage and seed zone delineation within an altitudinal transect of *Pinus devoniana (P. michoacana)* in Mexico. *Silvae Genética*, 57(3): 165–170. https://www.thuenen.de/media/institute/fg/PDF/Silvae_Genetica/2008/Vol._57_Heft_3/57_3_165.pdf

Sáenz-Romero, C., Rehfeldt, G.E., Soto-Correa, J.C.,

Aguilar-Aguilar, S., Zamarripa-Morales, V. & López-Upton, J. 2012. Altitudinal genetic variation among *Pinus pseudostrobus* populations from Michoacán, México. Two location shadehouse test results. *Revista Fitotecnia Mexicana*, 35(2): 111120. doi: 10.35196/rfm.2012.2.111

Sáenz-Romero, C., Lindig-Cisneros, R.A., Joyce, D.G., Beaulieu, J., St Clair, J.B. & Jaquish, B.C. 2016. Assisted migration of forest populations for adapting trees to climate change. *Revista Chapingo serie ciencias forestales y del ambiente*, 22(3): 303–323. doi: 10.5154/r.rchscfa.2014.10.052

Sáenz-Romero, C., Lamy, J.B., Ducousso, A., Musch, B., Ehrenmann, F., Delzon, S., Cavers, S. *et al*. 2017. Adaptive and plastic responses of *Quercus petraea* populations to climate across Europe. *Global Change Biology*, 23(7): 2831–2847. doi: 10.1111/gcb.13576

Sáenz-Romero, C., O'Neill, G., Aitken, S.N. & Lindig-Cisneros, R. 2021. Assisted migration field tests in Canada and Mexico: lessons, limitations, and challenges. *Forests*, 12(1): 9–27. https://dx.doi.org/10.3390/f12010009doi: 10.3390/f12010009

Sáenz-Romero, C., Osuna-Vallejo, V., Herrejón-Calderón, P., Pérez-Cruz, L.A., Joaquín-Juan, M.G., Cruzado-Vargas, A.L., O'Neill, G.A. *et al.* 2024. Establishing monarch butterfly overwintering sites for future climates: *Abies religiosa* upper altitudinal limit expansion by assisted migration. *Frontiers in Forests and Global Change* 7:1440517. doi: 10.3389/ffgc.2024.1440517

Sáenz-Romero, C. 2024. Arriving at a tipping point for worldwide forest decline due to accelerating climatic change. *The Forestry Chronicle*, 100(1):1-3 doi: 10.5558/tfc2024-003

Schmidt, L. 2000. *Guide to handling of tropical and subtropical forest seed*. Humlebaek, Denmark, Danida Forest Seed Centre. ISBN 87-982428-6-5

SAFORGEN (Sub-Saharan African Forest Genetic Resources Programme). 2011. *The SAFORGEN network*. SAFORGEN. ISBN 978-84-694-3166-5. http://hdl.handle.net/10532/1679

Salinas, N., Cosio, E. G., Silman, M., Meir, P., Nottingham, A. T., Roman-Cuesta, R. M. & Malhi, Y. 2021. Editorial: Tropical Montane Forests in a Changing Environment. *Frontiers in Plant Science*, 12.

Sambuichi, R.H.R. & Haridasan, M. 2007. Recovery of species richness and conservation of native Atlantic forest trees in the cacao plantations of southern Bahia in Brazil. *Biodiversity and Conservation*, 16: 3681–3701. doi: 10.1007/s10531-006-9017-x

Sandercock, A.M., Westbrook, J.W., Zhang, Q., Johnson, H.A., Saielli, T.M., Scrivani, J.A. *et al*. 2022. Frozen in time: Rangewide genomic diversity, structure, and demographic history of relict American chestnut populations. *Molecular Ecology*, 31(18): 4640-4655. doi: 10.1111/mec.16629

Santos del Blanco, L., Olsson, S., Budde, K. B., Grivet, D., González-Martínez, S. C., Alía, R., & Robledo-Arnuncio, J. J. 2022. On the feasibility of estimating contemporary effective population size (Ne) for genetic conservation and monitoring of forest trees. *Biological Conservation*, 273, 109704. doi: 10.1016/J.BIOCON.2022.109704

Schmidt, L.H., Barsotti, D., Moestrup, S., Abiyu, A., Graudal, L., Jamnadass, R., Dawson, I.K. & Lillesø, J.P.B. 2021. The Resources for Tree Planting Platform: delivering high-quality tree-planting material to growers. Nairobi, World Agroforestry. http://tree.worldagroforestry.org

Schmidtling, R.C & Hipkins, V. 1998. Genetic diversity in longleaf pine (*Pinus palustris*): influence of historical and prehistorical events. *Canadian Journal of Forest Research*, 28: 1135–1145. doi: 10.1139/x98-102

Schoen, D.J., Morgan, M.T. & Bataillon, T. 1996. How does self-pollination evolve? Inferences from floral ecology and molecular genetic variation. *Philosophical Transactions: Biological Sciences*, 1281–1290. doi: 10.1098/rstb.1996.0111

Schueler, S., Falk, W., Koskela, J., Lefèvre, F., Bozzano, M., Hubert, J., Kraigler, H. *et al*. 2014. Vulnerability of dynamic genetic conservation units of forest trees in Europe to climate change. *Global Change Biology*, 20(5): 1498–1511. doi: 10.1111/gcb.12476

Scoble, J. & Lowe, A.J. 2010. A case for incorporating phylogeography and landscape genetics into species distribution modelling approaches to improve climate adaptation and conservation planning. *Diversity and Distributions*, 16(3): 343–353. doi: 10.1111/j.1472-4642.2010.00658.x

Scotti-Saintagne, C., Bodénès, C., Barreneche, T., Bertocchi, E., Plomion, C. & Kremer, A. 2004. Detection of quantitative trait loci controlling bud burst and height growth in *Quercus robur* L. *Theoretical and Applied Genetics*, 109(8): 1648–1659. doi: 10.1007/s00122-004-1789-3

Scotti-Saintagne, C., de Sousa Rodrigues, A., Roig, A., Fady, B. 2024. A comprehensive strategy for the conservation of forest tree genetic diversity: an example with the protected *Pinus nigra* subsp. *salzmannii* (Dunal) Franco in France. *Conservation Genetics*, 25: 469–480. doi: 10.1007/s10592-023-01581-8.

Sedano, F., Lisboa, S., Duncanson, L., Ribeiro, N., Sitoe, A., Sahajpal, R., Hurtt, G. & Tucker, C. 2020. Monitoring intra and inter annual dynamics of forest degradation from charcoal production in Southern Africa with Sentinel – 2 imagery. *International Journal of Applied Earth Observation and Geoinformation*, 92. doi: 10.1016/j.jag.2020.102184.

Segelbacher, G., Bosse, M., Burger, P., Galbusera, P., Godoy, J.A., Helsen, P., Hvilsom, C. *et al*. 2022. New developments in the field of genomic technologies and their relevance to conservation management. *Conservation Genetics*, 23: 217–242. doi: 10.1007/s10592-021-01415-5

Serra-Varela, M.J., Alía, R., Daniels, R.R., Zimmermann, N.E., Gonzalo-Jiménez, J. & Grivet, D. 2017. Assessing vulnerability of two Mediterranean conifers to support genetic conservation management in the face of climate change. *Diversity and Distributions*, 23(5): 507–516. doi: /10.1111/ddi.12544

Sghaier-Hammami, B., Redondo-López, I., Valero-Galvàn, J. & **Jorrín-Novo, J.V.** 2015. Protein profile of cotyledon, tegument, and embryonic axis of mature acorns from a non-orthodox plant species: *Quercus ilex*. *Planta*, 243: 369–396. doi: 10.1007/s00425-015-2404-3

Shackleton, C.M. & de Vos, A. 2022. How many people globally actually use non-timber forest products? *Forest Policy and Economics*, 135: 102659. doi: 10.1016/j.forpol.2021.102659

Shafer, A.B., Wolf, J.B., Alves, P.C., Bergström, L., Bruford, M.W., Brännström, I., Colling, G. *et al.* 2015. Genomics and the challenging translation into conservation practice. *Trends in Ecology & Evolution*, 30(2): 78–87. doi: 10.1016/j.tree.2014.11.009

Shah, K.K., Tiwari, I., Modi, B., Pandey, H.P., Subedi, S. & Shrestha, J. 2021. Shisham (*Dalbergia sissoo*) decline by dieback disease, root pathogens and their management: a review. *Journal of Agriculture and Natural Resources*, 4(2): 255–272. doi: 10.3126/janr.v4i2.33915

Shanahan, M., Saengcharnchai, S., Atkinson, J. & Ganz, D. 2021. *Regional Assessment of Forest Education in Asia and the Pacific*. Rome, FAO. https://www.fao.org/3/cb6215en/cb6215en.pdf

Sharik, T., & Saracina, R. 2021. *Regional Assessment of Forest Education in North America (Canada and the United States)*. UBC Faculty of Forestry. Rome, FAO. https://www.fao.org/3/cb6741en/cb6741en.pdf

Shaw, R.E., Farquharson, K.A., Bruford, M.W., Coates, D.J., Elliott, C.P. *et al.* 2025. Global meta-analysis shows action is needed to halt genetic diversity loss. *Nature*. doi: 10.1038/s41586-024-08458-x

Shen, Y., Li, Y., Xu, D., Yang, C., Li, C. & Luo, K. 2018. Molecular cloning and characterization of a brassinosteriod biosynthesis-related gene PtoDWF4 from *Populus tomentosa*. *Tree Physiology,* 38(9): 1424–436. doi: 10.1093/treephys/tpy027

Shono, K. & Jonsson, Ö. 2022. Global progress towards sustainable forest management: bright spots and challenges. *International Forestry Review*, 24(1): 85–97. doi: 10.1505/146554822835224856

Shu, J. & Wang, H. 2015. Pests and diseases of bamboo. In: W. Liese & M. Koehl, eds. *Bamboo,* *the plant and its uses*, pp. 175–192. Heidelberg, Germany, Springer Verlag, Tropical Forestry Series.

Shyamsundar, P., Cohen, F., Boucher, T.M., Kroeger, T., Erbaugh, J.T., Waterfield, G., Clarke, C. *et al*. 2022. Scaling smallholder tree cover restoration across the tropics. *Global Environmental Change*, 76: article 102591. doi: 10.1016/j.gloenvcha.2022.102591

Šijačić-Nikolić, M., Nonić, M., Lalović, V., Milovanović, J., Nedeljković, J. & Nonić, D. 2017. Conservation of forest genetic resources: Key stakeholders' attitudes in forestry and nature protection. *Genetika*, 49(3): 875–890. doi: 10.2298/gensr1703875s

Šijačić-Nikolić, M., Milovanović, J. & Nonić, M., eds. 2019. *Forests of southeast Europe under a changing climate: conservation of genetic resources*. Berlin/Heidelberg, Germany, Springer International Publishing. https://link.springer.com/book/10.1007/978-3-319-95267-3

Silva, H.G., Sobral, R.S., Magalhães, A.P., Morais-Cecílio, L. & Costa, M.M.R. 2020. Genome-wide identification of epigenetic regulators in *Quercus suber* L. *International Journal of Molecular Sciences*, 21(11): 3783. doi: 10.3390/ijms21113783

Simler-Williamson, A.B., Rizzo, D.M. & Cobb, R.C. 2019. Interacting effects of global change on forest pest and pathogen dynamics. *Annual Review of Ecology, Evolution and Systematics*, 50: 381–403. doi: 10.1146/annurev-ecolsys-110218-024934

Simonin, K.A. & Roddy, A.B. 2018. Genome downsizing, physiological novelty, and the global dominance of flowering plants. *PLoS Biology*, 16(1), e2003706. doi: 10.1371/journal.pbio.2003706

Singleton, G.R., Belmain, S.R., Brown, P.R. & Hardy, B. eds. 2010. *Rodent outbreaks: Ecology and impacts*. Manila, International Rice Research Institute.

Skrøppa, T. & Fjellstad, K.B. 2017. Conservation of forest genetic resources in Norway in a climate change perspective. *In* M.R. Ahuja & S.M. Jain. eds. *Biodiversity and conservation of woody plants*, pp. 129–153. Cham, Switzerland, Springer.

Slatkin, M. 1987. Gene flow and the geographic structure of natural populations. *Science*, 236 (4803): 787–792. doi: 10.1126/science.3576198

Slavov, G.T., DiFazio, S.P., Martin, J., Schackwitz, W., Muchero, W., Rodgers-Melnick, E. *et al.* 2012. Genome resequencing reveals multiscale geographic structure and extensive linkage disequilibrium in the forest tree *Populus trichocarpa*. *The New Phytologist*, 196(3): 713–725. doi: 10.1111/j.1469-8137.2012.04258.x

Slik, J.W.F., Arroyo-Rodríguez, V., Aiba, S.-I., Alvarez-Loayza, P., Alves, L.F., Ashton, P., Balvanera, P. *et al*. 2015. An estimate of the number of tropical tree species. *Proceedings of the National Academy of Sciences*, 112(24): 7472–7477. doi: 10.1073/pnas.1423147112

Smith, C., Baker, J.C.A. & Spracklen, D.V. 2023. Tropical deforestation causes large reductions in observed precipitation. *Nature*, 615: 270–275. doi: 10.1038/s41586-022-05690-1

Sniezko, R.A. & Nelson, C.D. 2022. Resistance breeding against tree pathogens. In: F.O. Asiegbu & A. Kovalchuk, eds. *Forest Microbiology*, Vol. 10. pp. 159–175. Academic Press. doi: 10.1016/B978-0-323-85042-1.00007-0

Snook, L., Alves, T., Sousa, C., Loo, J., Gratzer, G., Duguma, L., Schrotter, C. *et al.* 2015. Relearning traditional knowledge to achieve sustainability: honey gathering in the miombo woodlands of northern Mozambique. XIV World Forestry Congress, Durban, South Africa, 7-11 September 2015. http://foris.fao.org/wfc2015/api/file/552e8b8e9e00c2f116f8eac2/contents/028c3429-30dd-4b71-856b-22ea44d4849c.pdf

Solberg, S. Ø., Yndgaard, F., Andreasen, C., Von Bothmer, R., Loskutov, I. G., & Asdal, Å. 2020. Long-term storage and longevity of orthodox seeds: A systematic review. *Frontiers in Plant Science*, 11: 1007. doi: 10.3389/fpls.2020.01007

Soliani, C., Umaña, F., Mondino, V., Thomas, E., Pastorino, M.J., Gallo, L.A. & Marchelli, P. 2017. Zonas genéticas de lenga y ñire en Argentina, y su aplicación en la conservación y manejo de los recursos forestales. Bariloche, Argentina, Instituto Nacional de Tecnología Agropecuaria (INTA). ISBN: 978-987-521-871-0

Soliño, M., Alía, R. & Agúndez, D. 2020. Citizens' preferences for research programs on forest genetic resources: A case applied to *Pinus pinaster* Ait. in Spain. *Forest Policy and Economics*, 118: 102255. doi: 10.1016/j.forpol.2020.102255

Sollars, E.S., Harper, A.L., Kelly, L.J., Sambles, C.M., Ramirez-Gonzalez, R.H., Swarbreck, D. *et al*. 2017. Genome sequence and genetic diversity of European ash trees. *Nature*, 541(7636): 212–216.

Sonwa, D.J., Nkongmeneck, B.A., Weise, S F., Tchatat, M., Adesina, A.A. & Janssens, M.J.J. 2007. Diversity of plants in cocoa agroforests in the humid forest zone of Southern Cameroon. *Biodiversity and Conservation*, 16: 2385–2400. doi:10.1007/s10531-007-9187-1

Sorensen, F.C. & Miles, R.S. 1974. Self-pollination effects on Douglas-fir and ponderosa pine seeds and seedlings. *Silvae Genetica*, 23(5), 135–138.

Sorrenti, S. 2017. *Non-wood forest products in international statistical systems*. Non-wood Forest Products Series no. 22. Rome, FAO.

Soulé**, M.,** 1980. Thresholds for survival: maintaining fitness and evolutionary potential. *In* M.E. Soulé & B.A. Wilcox, eds. *Conservation biology: an evolutionary-ecological perspective*, pp. 151–169. Sunderland, USA, Sinauer Associates.

St. Clair, J.B., Richardson, B.A., Stevenson-Molnar, N., Howe, G.T., Bower, A.D., Erickson, V.J., Ward, B. *et al*. 2022. Seedlot Selection Tool and Climate-Smart Restoration Tool: Web-based tools for sourcing seed adapted to future climates. *Ecosphere*, 13(5): 1–18. doi: 10.1002/ecs2.4089

Stalker, H.T., Warburton, M.L. & Harlan, J.R. 2021. *Harlan's crops and man: people, plants and their domestication*. Third Edition. Hoboken, USA. American Society of Agronomy, Crop Science Society of America and John Wiley & Sons. doi: 10.1002/9780891186342

Standurf, J.A., Ivetić, V. & Dumroese, R.K. 2024. Framing recent advances in assisted migration of trees: A Special Issue. *Forest Ecology and Management*, 551: 121552. doi: 10.1016/j.foreco.2023.121552

Steiner, K.C., Westbrook, J.W., Hebard, F.V., Georgi, L.L., Powell, W.A. & Fitzsimmons, S.F. 2017. Rescue of American chestnut with extraspecific genes following its destruction by a naturalized pathogen. *New Forests*, 48: 317–336. doi: 10.1007/s11056-016-9561-5

Stévart, T., Dauby, G., Lowry, P.P. II, Blach-Overgaard, A., Droissart, V., Harris, D.J., Mackinder, B.A. *et al.* 2019. A third of the tropical African flora is potentially threatened with extinction. *Sci Adv*, 5: eaax9444. doi: 10.1126/sciadv.aax9444

Stewart, J.F., Will, R.E., Crane, B.S. & Nelson, C.D. 2016. The genetics of shortleaf pine (*Pinus echinata mill.*) with implications for restoration and management. *Tree Genetics and Genomes*, 12: 98. doi: 10.1007/s11295-016-1052-5

Stocks, J. J., Metheringham, C. L., Plumb, W. J., Lee, S. J., Kelly, L. J., Nichols, R. A., & Buggs, R. J. 2019. Genomic basis of European ash tree resistance to ash dieback fungus. *Nature ecology & evolution*, *3*(12): 1686-1696. doi: 10.1038/s41559-019-1036-6

Stoian, D., Rodas, A., Butler, M., Monterroso, I. & Hodgdon, B. 2018. *Forest concessions in Petén, Guatemala: A systematic analysis of the socioeconomic performance of community enterprises in the Maya Biosphere Reserve*. Bogor, Indonesia, Center for International Forestry Research. https://www.cifor.org/library/7163

Suarez-Gonzalez, A., Hefer, C.A., Christe, C., Corea, O., Lexer, C., Cronk, Q.C. *et al*. 2016. Genomic and functional approaches reveal a case of adaptive introgression from *Populus balsamifera* (balsam poplar) in P. átrichocarpa (black cottonwood). *Molecular Ecology*, 25(11): 2427–2442. doi: 10.1111/mec.13539

Suarez-Gonzalez, A., Lexer, C. & Cronk, Q.C. 2018. Adaptive introgression: a plant perspective. *Biology Letters*, 14(3): 20170688. doi: 10.1098/rsbl.2017.0688

Svenning, J.C., Eiserhardt, W.L., Normand, S., Ordonez, A. & Sandel, B. 2015. The influence of paleoclimate on present-day patterns in biodiversity and ecosystems. *Annual Review of Ecology, Evolution, and Systematics*, 46: 551–572. doi: 10.1146/annurev-ecolsys-112414-054314

Tamaki, I., Setsuko, S. & Tomaru, N. 2016. Genetic diversity and structure of remnant *Magnolia stellata* populations affected by anthropogenic pressures and a conservation strategy for maintaining their current genetic diversity. *Conservation Genetics*, 17(3): 715–725. doi: 10.1007/s10592-016-0817-6

Tchebakova, N.M., Rehfeldt, G.E. & Parfenova, E.I. 2005. Impacts of climate change on the distribution of *Larix* spp. and Ledeb. and *Pinus sylvestris* and their climatypes in Siberia. *Mitigation and Adaptation Strategies for Global Change*, 11(4): 861–882. doi: 10.1007/s11027-005-9019-0

TEAKNET (International Teak Information Network). 2020. *TEAKNET home page*. [Cited 23 January 2024[. https://teaknet.org/

TEEB. 2018. *TEEB for Agriculture & Food: Scientific and Economic Foundations*. Geneva, UN Environment.

Teixeira, J.C. & Huber, C.D. 2021. The inflated significance of neutral genetic diversity in conservation genetics. *Proceedings of the National Academy of Sciences*, 118(10): e2015096118. doi: 10.1073/pnas.201509611

Tejedor Garavito, N., Newton, A.C., Golicher, D. & Oldfield, S. 2015. The relative impact of climate change on the extinction risk of tree species in the Montane Tropical Andes. *PLoS ONE*, 10(7): e0131388. doi: 10.1371/journal.pone.0131388

Thang, T. H., Thu, A. M. & Chen, J. 2020. Tree species of tropical and temperate lineages in a tropical Asian montane forest show different range dynamics in response to climate change. *Global Ecology and Conservation*, 22, e00973. doi: 10.1016/j.gecco.2020.e00973

Thomas, E., van Zonneveld, M., Loo, J., Hodgkin, T., Galluzzi, G., & van Etten, J. 2012. Present spatial diversity patterns of *Theobroma cacao* L. in the Neotropics reflect genetic differentiation in Pleistocene refugia followed by human-influenced dispersal. *PLoS ONE*, *7*(10). doi: 10.1371/journal.pone.0047676

Thomas, E., Alcázar Caicedo, C., McMichael, C.H., Corvera, R. & Loo, J. 2015. Uncovering spatial patterns in the natural and human history of Brazil nut (*Bertholletia excelsa*) across the Amazon Basin. *Journal of Biogeography*, 42(8): 1367–1382. doi: 10.1111/jbi.12540

Thomas, E., Valdivia, J., Alcázar Caicedo, C., Quaedvlieg, J., Wadt, L.H.O. & Corvera, R. 2017. NTFP harvesters as citizen scientists: Validating traditional and crowdsourced knowledge on seed production of Brazil nut trees in the Peruvian Amazon. *PLoS ONE*, 12(8): e0183743. doi: 10.1371/journal.pone.0183743

Tomlinson, P. B. 2006. The uniqueness of palms. *Botanical Journal of the Linnean Society*, 151: 5–14. doi: 10.1111/j.1095-8339.2006.00520.x

Tonellotto, M., Fehr, V., Conedera, M., Hunziker, M. & Pezzatti, G.B. 2022. Iconic but invasive: The public perception of the Chinese windmill palm (*Trachycarpus fortunei*) in Switzerland. *Environmental Management*, 70: 618–632. doi: 10.1007/s00267-022-01646-3

Triplett, J.K. & Clark, L.G. 2021. Hybridization in the temperate bamboos (Poaceae: Bambusoideae: Arundinarieae): A phylogenetic study using AFLPs and cpDNA sequence data. *Systematic Botany*, 46: 48–69. doi: 10.1600/036364421X16128061189503

Tsuruta, M., Maruyama, T.E., Ueno, S., Hasegawa, Y. & Moriguchi, Y. 2021. Marker-assisted selection for pollen-free somatic plants of sugi (Japanese cedar, *Cryptomeria japonica*): A simple and effective methodology for selecting male-sterile mutants with ms1-1 and ms1-2. *Frontiers In Plant Science*, 12: 748110. doi: 10.3389/fpls.2021.748110

Tudge, C. 2006. *The tree: a natural history of what trees are, how they live, and why they matter*. New York, USA, Three Rivers Press.

Turner-Skoff, J.B., Paist, S., Byrne, A. & Westwood, M. 2022. ArbNet: 10 years of fostering collaborations, furthering professionalism, and advancing the planting and conservation of trees through the global network of arboreta. *Plants People Planet*, 4: 128–135. doi: 10.1002/ppp3.10228

Tuskan, G.A., Difazio, S., Jansson, S., Bohlmann, J., Grigoriev, I., Hellsten, U., Putnam, N. *et al.* 2006. The genome of black cottonwood, *Populus trichocarpa* (Torr. & Gray). *Science*, 313(5793): 1596–1604.

Tweddle, J.C., Dickie, J.B., Baskin, C.C. & Baskin, J.M. 2003. Ecological aspects of seed desiccation sensitivity. *J Ecol*, 91: 294–304. doi: 10.1046/j.1365-2745.2003.00760.x

Tzedakis, P. C., Emerson, B. C. & Hewitt, G. M. 2013. Cryptic or mystic? Glacial tree refugia in northern Europe. *Trends in Ecology & Evolution*, 28(12): 696–704. doi: 10.1016/j.tree.2013.09.001

Umarani, R., Kanthaiya Aadhavan, E. & Mohamed Faisal, M. 2015. Understanding poor storage potential of recalcitrant seeds. *Curr Sci*, 108: 2023–2034.

UN (General Assembly). 2017. United Nations Strategic Plan for Forests 2017–2030. A/RES/71/285.

UN. 2007. *Non-legally binding instrument on all types of forests*. Resolution adopted by the General Assembly on 17 December 2007. A/RES/62/98. New York, USA. https://documents.un.org/doc/undoc/gen/n07/469/65/pdf/n0746965.pdf

UN. 2015. Transforming our world – The 2030 Agenda for Sustainable Development. A/RES/70/1. Resolution adopted by the General Assembly on 25 September 2015. [Cited 26 January 2023]. https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E

UN. 2017. *United Nations Strategic Plan for Forests 2017–2030*. Resolution adopted by the General Assembly on 27 April 2017. A/RES/71/285. New York, USA.

UN. 2023. The Sustainable Development Goals Report: Special edition. United Nations. New York, USA. https://unstats.un.org/sdgs/report/2023/The-Sustainable-Development-Goals-Report-2023.pdf

UNEP-WCMC & IUCN. 2023. Protected Planet: The World Database on other effective area-based conservation measures (WD-OECM), Cambridge, UK. Cited June 2023. doi:10.34892/ndcc-cs86

UNESCO. Undated. TVETipedia Glossary. United Nations Educational, Scientific and Cultural Organization (UNESCO)–UNEVOC. [Cited 30 December 2022]. https://unevoc.unesco.org/home/TVETipedia+Glossary/lang=en/filt=all/id=474

UNFF. 2021. *The Global Forest Goals Report 2021*. Secretariat of the United Nations Forum on Forests, United Nations Department of Economic and Social Affairs. New York, USA.

Ungerer, M.C., Johnson, L.C. & Herman, M.A. 2008. Ecological genomics: understanding gene and genome function in the natural environment. *Heredity*, 100(2): 178–183. doi: 10.1038/sj.hdy.6800992

Valdés, Y.C., Shukla, M.R., Vega, M.E.G. & **Saxena, P.K.** 2021. Improved conservation of coffee (*Coffea arabica* L.) germplasm via micropropagation and cryopreservation. *Agronomy*, 11: 1861. doi: 10.3390/agronomy11091861

van Breugel, P., Kindt, R., Lillesø, J.P.B., Bingham, M., Demissew, S., Dudley, C., Friis, I. *et al*. 2015. *Potential natural vegetation map of Eastern Africa (Burundi, Ethiopia, Kenya, Malawi, Rwanda, Tanzania, Uganda and Zambia). Version 2.0.* Copenhagen, Forest and Landscape (Denmark) and Nairobi, World Agroforestry Centre (ICRAF). http://vegetationmap4africa.org

van Dijk, A. D. J., Kootstra, G., Kruijer, W., & de Ridder, D. 2021. Machine learning in plant science and plant breeding. *iScience*, *24*(1): 101890. doi: 10.1016/J.ISCI.2020.101890

van Zonneveld, M., Thomas, E., Castañeda-Álvarez, N.P., Van Damme, V., Alcazar, C., Loo, J. *et al*. 2018. Tree genetic resources at risk in South America: A spatial threat assessment to prioritize populations for conservation. *Diversity & Distributions,* 24(6): 718–729. doi: 10.1111/ddi.12724

Vasquez-Gross, H.A., Yu, J.J., Figueroa, B., Gessler, D.D., Neale, D.B. & Wegrzyn, J.L. 2013.

CartograTree: connecting tree genomes, phenotypes and environment. *Molecular Ecology Resources*, 13(3): 528–537. doi: 10.1111/1755-0998.12067

Vidal, K.V.A., Souza, M.J.O., Welker, C.A.D., Oliveira, I.L.C., Clark, L.G. & Oliveira, R.P. 2023. A new species of *C.* subg. *Chusquea* (Poaceae: Bambusoideae) endemic to the Espinhaço Range, Brazil. *Phytotaxa*, 579: 255–266. doi: 10.11646/phytotaxa.579.4.3

Vie, J.-C., Hilton-Taylor, C. & Stuart, S.N. eds. 2009. *Wildlife in a changing world: an analysis of the 2008 IUCN Red List of Threatened Species*. Gland, Switzerland, IUCN.

Vinceti, B., Manica, M., Lauridsen, N., Verkerk, P.J., Lindner, M. & Fady, B. 2020. Managing forest genetic resources as a strategy to adapt forests to climate change: perceptions of European forest owners and managers. *European Journal of Forest Research*, 139: 1107–1119. doi: 10.1007/s10342-020-01311-6

Vinson, C. C., Mangaravite, E., Sebbenn, A. M. & Lander, T. A. 2018. Using molecular markers to investigate genetic diversity, mating system and gene flow of Neotropical trees. *Brazilian Journal of Botany*, 41(2): 481–496. doi: 10.1007/s40415-018-0472-x

Vlam, M., van der Sleen, P., Groenendijk, P. & Zuidema, P.A. 2017. Tree age distributions reveal large-scale disturbance-recovery cycles in three tropical forests. *Frontiers in Plant Science*, 7: 1984. doi: 10.3389/fpls.2016.01984

Volk, G. M., Bonnart, R., Shepherd, A., Yin, Z., Lee, R., Polek, M. & Krueger, R. 2017. Citrus cryopreservation: viability of diverse taxa and histological observations. *Plant Cell Tissue Organ Cult*, 128: 327–334. doi: 10.1007/s11240-016-1112-4

Vorontsova, M.S., Clark, L.G., Dransfield, J., Govaerts, R. & Baker, W.J. 2016. *World checklist of bamboos and rattans*. INBAR Technical Report No. 37. Beijing, International Network of Bamboo and Rattan. http://resource.inbar.int/download/showdownload.php?lang=cn&id=167759

Vranckx, G.U.Y., Jacquemyn, H., Muys, B. & Honnay, O. 2012. Meta-analysis of susceptibility of woody plants to loss of genetic diversity through habitat fragmentation. *Conservation Biology*, 26(2): 228–237. doi: 10.1111/j.1523-1739.2011.01778.x

Wachowiak, W., Salmela, M.J., Ennos, R.A., Iason, G. & Cavers, S. 2011. High genetic diversity at the extreme range edge: nucleotide variation at nuclear loci in Scots pine (*Pinus sylvestris* L.) in Scotland. *Heredity*, 106(5): 775–787.

Waiboonya, P., Elliott, S. & Tiansawat, P. 2019. Seed storage behaviour of native forest tree species of northern Thailand. *Environ Asia*, 12: 104–111. doi: 10.14456/ea.2019.50

Walas, Ł., Sobierajska, K., Ok, T., Dönmez, A.A., Kanoğlu, S.S., Dagher-Kharrat *et al*. 2019. Past, present, and future geographic range of an oro-Mediterranean Tertiary relict: The *Juniperus drupacea* case study. *Regional Environmental Change*, 19(5): 1507–1520. doi: 10.1007/s10113-019-01489-5

Wan, S., Li, C., Ma, X. & Luo, K. 2017. PtrMYB57 contributes to the negative regulation of anthocyanin and proanthocyanidin biosynthesis in poplar. *Plant Cell Reports,* 36(8): 1263–1276. doi: 10.1007/s00299-017-2151-y

Wang, T., Smets, P., Chourmouzis, C., Aitken, S.N. & Kolotelo, D. 2020. Conservation status of native tree species in British Columbia. *Global Ecology and Conservation*, 24: e01362. doi: 10.1016/j.gecco.2020.e01362

Wanger, F., Below, R., De Klerk, P., Dilcher, D.I., Joosten, H., Kürschner, W.M. & Visscher, H. 1996. A natural experiment on plant acclimation: Lifetime stomatal frequency response of an individual tree to annual atmospheric CO2 increase. *Proceedings of the National Academy of Sciences*, 93: 11705–11708. doi: 10.1073/pnas.93.21.11705

Ward, M., Dick, C. W., Gribel, R. & Lowe, A. J. 2005. To self, or not to self... a review of outcrossing and pollen-mediated gene flow in neotropical trees. *Heredity*, 95: 246–54. doi: 10.1038/sj.hdy.6800712

Wawrzyniak, M.K., Michalak, M. & **Chmielarz, P.**

2020. Effect of different conditions of storage on seed viability and seedling growth of six European wild fruit woody plants. *Ann For Sci*, 77: 1–20. doi: 10.1007/s13595-020-00963-z

Wegrzyn, J.L., Liechty, J.D., Stevens, K.A. *et al.* 2014. Unique features of the loblolly pine (*Pinus taeda* L.) megagenome revealed through sequence annotation. *Genetics*, 196: 891–909. doi: 10.1534/genetics.113.159996

Wegrzyn, J.L., Staton, M. A., Street, N. R., Main, D., Grau, E., Herndon, N., Buehler, S. *et al.* 2019. Cyberinfrastructure to Improve Forest Health and Productivity: The Role of Tree Databases in Connecting Genomes, Phenomes, and the Environment. *Frontiers in Plant Science*, 10. doi: 10.3389/fpls.2019.00813

Wegrzyn, J.L., Falk, T., Grau, E., Buehler, S., Ramnath, R. & Herndon, N. 2020. Cyberinfrastructure and resources to enable an integrative approach to studying forest trees. *Evolutionary Applications*, 13: 228–241. doi: 10.1111/eva.12860

Wehenkel, C., Mariscal-Lucero, S.D.R., Jaramillo-Correa, J.P., López-Sánchez, C.A., Vargas-Hernández, J.J. & Sáenz-Romero, C. 2017. Genetic diversity and conservation of Mexican forest trees. In: M.R. Ahuja & S. Mohan Jain, eds. *Biodiversity and conservation of woody plants*, pp. 37–67. Cham, Switzerland, Springer. doi: 10.1007/978-3-319-66426-2

Wetterstrand, K. A. 2020. *DNA sequencing costs: data from the NHGRI Genome Sequencing Program (GSP).* National Human Genome Research Institute. www.genome.gov/sequencingcostsdata

Wheeler, M.A., Byrne, M. & McComb, J.A. 2003. Little genetic differentiation within the dominant forest tree *Eucalyptus marginata* (Myrtaceae) of south-western Australia. *Silvae Genetica*, 52: 254–25.

Whiteley, A.R., Fitzpatrick, S.W., Funk, W.C. & Tallmon, D.A. 2015. Genetic rescue to the rescue. *Trends in Ecology & Evolution*, 30(1): 42–49. doi: 10.1016/j.tree.2014.10.009

Whitlock, M.C. 2008. Evolutionary inference from QST. *Molecular Ecology*, 17(8): 1885–1896.

Whittet, R., Cavers, S., Cottrell, J., & Ennos, R. 2016. Seed sourcing for woodland creation in an era of uncertainty: an analysis of the options for Great Britain. *Forestry*, 90(2): 163–173. doi: 10.1093/forestry/cpw037

Widjaja, E. 2019. *The spectacular Indonesian bamboos*. Jakarta, Indonesian Institute of Sciences. https://obor.or.id/the-spectacular-indonesian-bamboos

Wilhelm, E. 2005. Micro- and micropropagation of forest trees. In: T. Geburek & J. Turok, eds. *Conservation and management of forest genetic resources in Europe*, pp. 623–650. Zvolen, Slovakia, Arbora Publishers.

Wilkie, M.L., Holmgren, P. & Castañeda, F. 2003. *Sustainable forest management and the ecosystem approach: two concepts, one goal*. Forest Management Working Papers, Working Paper FM 25. Forest Resources Development Service, Forest Resources Division. Rome, FAO. https://www.fao.org/3/J1244e/J1244e.pdf

Willis, K. J. 2009. Evolution and Function of Earth's Biomes: Temperate Forests. In: V. Cilek, ed. *Earth System: History and Natural Variability*, Volume III, pp. 164–190.Oxford, EOLSS publishers and UNESCO.

Woodcock, P., Cottrell, J.E., Buggs, R.J. & Quine, C.P. 2018. Mitigating pest and pathogen impacts using resistant trees: a framework and overview to inform development and deployment in Europe and North America. *Forestry: An International Journal of Forest Research*, 91(1): 1–16. doi: 10.1093/forestry/cpx031

Woodward, F. I., Lomas, M. R. & Kelly, C. K. 2004. Global Climate and the Distribution of Plant Biomes. *Philosophical Transactions: Biological Sciences*, 359(1450): 1465–1476. doi: 10.1098/rstb.2004.1525

World Agroforestry. 2023a. *Agroforestry Species Switchboard 3.0*. Cited 24 January 2024. https://apps.worldagroforestry.org/products/switchboard/

World Agroforestry. 2023b. *Global Tree Knowledge Platform, World Agroforestry | Transforming Lives and Landscapes with Trees*. Cited 24

January 2024. https://www.worldagroforestry.org/tree-knowledge

World Resources Institute. 2019. *Creating a sustainable food future. A menu of solutions to feed nearly 10 billion people by 2050.* https://www.wri.org/research/creating-sustainable-food-future.

Wright, J.S., Fu, R., Worden, J.R., Chakraborty, S., Clinton, N.E., Risi, C., Sun, Y. & Yin, L. 2017. Rainforest-initiated wet season onset over the southern Amazon. *Proceedings of the National Academy of Sciences*, 114(32): 8481–8486. doi: 10.1073/pnas.1621516114

Wyse, S.V. & Dickie, J.B. 2017. Predicting the global incidence of seed desiccation sensitivity. *J Ecol*, 105: 1082–1093. doi: 10.1111/1365-2745.12725

Wyse, S.V. & Dickie, J.B. 2018. Taxonomic affinity, habitat and seed mass strongly predict seed desiccation response: a boosted regression trees analysis based on 17,539 species. *Ann Bot*, 121: 71–83. doi: 10.1093/aob/mcx128

Wyse, S.V., Dickie, J.B. & Willis, K.J. 2018. Seed banking not an option for many threatened plants. *Nat Plants*, 4: 848–850. doi: 10.1038/s41477-018-0298-3

Xiao, Y., Xiao, Q. & Sun, X. 2020. Ecological risks arising from the impact of large-scale afforestation on the regional water supply balance in southwest China. *Sci Rep*, 10: 1–10. doi :10.1038/s41598-020-61108-w

Xu, C., Fu, X., Liu, R., Guo, L., Ran, L., Li, C., Tian, Q. *et al.* 2017. PtoMYB170 positively regulates lignin deposition during wood formation in poplar and confers drought tolerance in transgenic Arabidopsis. *Tree Physiology,* 37(12): 1713–1726. doi: 10.1093/treephys/tpx09

Xu, W. & Prescott, C. E. 2024. Can assisted migration mitigate climate-change impacts on forests? *Forest Ecology and Management*, 556: 121738. doi: 10.1016/j.foreco.2024.121738

Xu, W.-B., Guo, W.-Y., Serra-Diaz, J.M., Schrodt, F., Eiserhardt, W.L., Enquist, B.J., Maitner, B.S. *et al*. 2023. Global beta-diversity of angiosperm trees is shaped by Quaternary climate change. *Science Advances*, 9: eadd8553. doi: 10.1126/sciadv.add85

Yanchuk, A.D. 2001. A quantitative framework for breeding and conservation of forest tree genetic resources in British Columbia. *Canadian Journal of Forest Research*, 31(4): 566–576. doi: 10.1139/x00-133

Yang, H., Li, J., Milne, R.I., Tao, W., Wang, Y., Miao, J. *et al.* 2022. Genomic insights into the genotype–environment mismatch and conservation units of a Qinghai–Tibet Plateau endemic cypress under climate change. *Evolutionary Applications*, 15(6): 919. doi: 10.1111/eva.13377

Yang, L., Zhao, X., Ran, L., Li, C., Fan, D. & Luo, K. 2017. PtoMYB156 is involved in negative regulation of phenylpropanoid metabolism and secondary cell wall biosynthesis during wood formation in poplar. *Scientific Reports,* 7: 41209. doi: 10.1038/srep41209

Yao, Y., Wang, X., Zeng, Z., Liu, Y., Peng, S., Zhu, Z. & Piao, S. 2016. The effect of afforestation on soil moisture content in northeastern China. *PLoS One*, 11: e0160776. doi: 10.1371/journal.pone.0160776

Yemshanov, D., Koch, F.H., Ben-Haim, Y., Downing, M., Sapio, F. & Siltanen, M. 2013. A new multicriteria risk mapping approach based on a multiattribute frontier concept. *Risk Analysis*, 33(9): 1694–1709. doi: 10.1111/risa.12013

Yuan, J.-L., Yue, J.-J., Gu, X.-P. & Lin, C.-S. 2017. Flowering of woody bamboo in tissue culture systems. *Frontiers in Plant Science*, Plant Physiology Section, 8. doi: 10.3389/fpls.2017.01589

Zechini, A.A., Lauterjung, M.B., Candido-Ribeiro, R., Montagna, T., Bernardi, A.P., Hoeltgebaum, M.P. *et al.* 2018. Genetic conservation of Brazilian Pine (*Araucaria angustifolia*) through traditional land use. *Economic Botany*, 72(2): 166–179. doi: 10.1007/s12231-018-9414-6

Zelli, F., Nielsen, T. & Dubber, W. 2019. Seeing the forest for the trees: identifying discursive convergence and dominance in complex REDD+ governance. *Ecology and Society*, 24(1):10. doi:

10.5751/ES-10632-240110

Zewdie, B., Tack, A.J.M., Ayalew, B., Wondafrash, M., Nemomissa, S. & Hylander, K. 2022. Plant biodiversity declines with increasing coffee yield in Ethiopia's coffee agroforests. *Journal of Applied Ecology*, 59: 1198–1208. doi: 10.1111/1365-2664.14130

Zhang, K., Zhang, Y., Sun, J., Meng, J. & Tao, J. 2021. Deterioration of orthodox seeds during ageing: influencing factors, physiological alterations and the role of reactive oxygen species. *Plant Physiol Biochem*, 158: 475–485. doi: 10.1016/j.plaphy.2020.11.031

Zinck, J.W. & Rajora, O.P. 2016. Post-glacial phylogeography and evolution of a wide-ranging highly-exploited keystone forest tree, eastern white pine (*Pinus strobus*) in North America: single refugium, multiple routes. *BMC Evolutionary Biology*, 16(1): 56. doi: 10.1186/s12862-016-0624-1

Zomer, R.J., Trabucco, A., Coe, R., Place, F., van Noordwijk, M. & Xu, J.C. 2014. *Trees on farms: an update and reanalysis of agroforestry's global extent and socio-ecological characteristics*. ICRAF Working Paper No. 179. Nairobi, World Agroforestry Centre (ICRAF).

Zomer, R.J., Neufeldt, H., Xu, J., Ahrends, A., Bossio, D.A., Trabucco, A., van Noordwijk, M. & Wang, M. 2016. Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. *Scientific Reports*, 6: article 29987. doi: 10.1038/srep29987

Zomer, R.J., Bossio, D.A., Trabucco, A., Noordwijk, M. & Xu, J. 2022. Global carbon sequestration potential of agroforestry and increased tree cover on agricultural land. *Circular Agricultural Systems*, 2: 3 doi: 10.48130/CAS-2022-0003

Forests and woodlands provide a huge array of essential benefits for people and the planet – such as hosting biodiversity, supporting livelihoods, protecting soils, regulating water cycles and mitigating climate change. At the heart of such benefits are forest genetic resources: the heritable materials maintained within and among tree and other woody plant species that are of actual or potential economic, environmental, scientific or societal value. These genetic resources underpin the resilience, adaptability and productivity of forests and other tree-based systems, enabling them to withstand environmental stresses and thereby continue providing vital ecosystem services.

Drawing on data and information from 77 countries representing more than three-quarters of the world's forests, *The Second Report on the State of the World's Forest Genetic Resources* provides a global assessment of forest genetic resources. It highlights the crucial role of these resources for sustainable development and examines progress in implementing the Global Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources. The report reviews scientific advances and concludes with recommendations for continued action at the national, regional and global levels to ensure that forest genetic resources are sustainably managed for the benefit of current and future generations.

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