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Forest biomass potential for wood pellets production in the United States of America for exportation: a review

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ABSTRACT

This document presents a review that covers the United States potential biomass resource for exports compared to the current levels the European Union and United Kingdom receive, and addresses current and potential risks, opportunities and challenges to increasing the volume of imports regarding sustainability of forest ecosystems before climate change, current forest management, and other factors such as social, economic, conservation, and sustainability of natural resources in the United States, when producing forest biomass for wood pellet production in Southern United States. From this review, it can be concluded that the majority of forest biomass assessments projections showed that forest biomass from the Southeast of the USA for wood pellets production in 2030 could vary from 74 million dry tons up to 95 million dry tons depending on the increment on prices per dry ton, and for 2050 could range from 85 for low consumption scenario to 162 million dry tons for high consumption scenario using a conversion factor of 2 green tons per one ton of wood pellets. Research needs are also pointed out in the document.

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wood pellets; supply; demand; wood pellet markets

Introduction


The European Union (EU) since the early 2000s has been aiming to reduce greenhouse gas emissions and comply with the Kyoto Protocol to the United Nations Framework Convention on Climate Change [1] enacting several actions. At the end of 2008, the EU Commission agreed on legally binding targets (The UE's Renewable Energy Directive 2009/28/EC), by 2020, to cut greenhouse gas emissions by 20%, to establish a 20% share for renewable energy, and to improve energy efficiency by 20%. The directive established legally binding targets for each Member State to reach the EU target of a 20% share of renewable energy in 2020 [2, 3]. The EU Commission in 2014 [4] agreed on a greenhouse gas emission reduction target for domestic EU emissions of 40% in 2030 relative to emissions in 1990. This goal reduction in greenhouse emissions implied a greater share of renewable energy in the EU of at least 27% [4].

The EU directive (EU) 2018/2001 defines "energy from renewable sources or renewable energy as energy from renewable non-fossil sources, such as wind, solar (solar thermal and solar photovoltaic) geothermal energy, ambient energy, tide, wave and other ocean energy, hydro-power, biomass, landfill gas, sewage treatment plant gas, and biogas" [5]. Biomass is a renewable energy source derived from agriculture, forestry and industrial activities that involves different supply chains that produce biomass raw materials, to producers and suppliers of biomass-based fuels, products, and power, to the ultimate end-user markets [6]. The EU directive (EU) 2018/2001 defines biomass

as "the biodegradable fraction of products, waste and residues from biological origin from agriculture, including vegetal and animal substances, from forestry and related industries, including fisheries and aquaculture, as well as the biodegradable fraction of waste, including industrial and municipal waste of biological origin" [5]. According to Bioenergy Europe (2021) [7, 8] the main feedstock in the European Union is currently coming from the forest sector representing more than two thirds of the overall EU bioenergy consumption.

One of the products of forest biomass for bioenergy use is wood pellets. Chipping, shredding, and milling are typical first process steps to create a uniform material that is fed through a press containing holes of a uniform size [9]. Wood pellets are made up of raw material that is reduced to small pieces. The material is then pressed into a funnel shaped hole called a die and during this process the material compresses as the diameter of the die gets smaller. This compresses the material into a dense pellet. The compression and friction from this process creates heat which melts the wood. After this process is done, the pellet is allowed to cool. In the cooling process the lignins act as a glue binding the material producing a hard and strong pellet [10, 11].

The pelleting process converts finely ground materials into dense, free-flowing, durable pellets. A pellet has uniform product characteristics in terms of size with length and diameter from 13–19 mm and 6.3–6.4 mm respectively, its shape is cylindrical, and unit densities vary from 1125–1190 kg/m³ [12]. Wood pellets must have high energy density, which makes them suitable for both

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commercial and industrial heating applications. A pellet with low compression resistance tends to disintegrate easily, due to moisture adsorption [13].

The world trade of wood pellets as a renewable energy source has increased significantly since 2000. According to Statista (2022) [14] world wood pellets production has increased since 2000 from 1.7 million metric tons to 55.7 million metric tons in 2018. The global pellet production continued growing with an increase of 5% per year between 2019 and 2020. During the same period, the EU had a rate growth of 4% reaching a production of 18 million metric tons [15].

According to Calderon and Colla. [16] in 2018 world wood pellet consumption has increased to 35.14 million tons (excluding China, and when included China it totals 52.74 million tons). At the global level, industrial pellet consumption has increased by nearly 3 million tons from 2017 to 2018. Asia has had a continuous growth in wood pellet consumption during the last several years. South Korea and Japan have shown an increase of 39% and 86%, respectively for industrial consumption [16].

The EU is a major importer of wood pellets and plays an important role in the wood pellets market with half the global wood pellet trade taking place within the EU [17]. In 2018, the EU28 consumption increased by around 2 million tons in the industrial use of pellets mainly in the UK, and between 2019 and 2020 EU27 wood pellets consumption increased 4.5% [15].

Forest biomass is of prime importance to achieve climate and energy objectives to decrease the impacts of climate change. It will continue to be a reliable source of renewable energy into the future in order to achieve the EU Renewable Energy Directive targets, also with additional benefits such as security of energy supply, sustainable energy at affordable prices, promoting technological development and innovation, providing environmental, social and health benefits and employment, and regional development, especially in rural and isolated areas, in regions or territories with low population density or undergoing partial deindustrialization [5].

The EU biomass energy sector also has significant socio-economic impacts by offering about 700,000 direct and indirect jobs in the EU with a turnover of almost EUR 60 billion [18]. Although, the EU is the main wood pellets producer in the world [19], its consumption is higher than its production being also the biggest world wood pellets importer. This is because, there are some countries that are not able of covering their own wood pellets demand with their own forest biomass for energy production, and their own industry infrastructure, and they are importing wood pellets from several countries of the EU, Canada, and United States of America. For example EU27 wood pellets production in 2020 was 18.1 million tons and in the same year the consumption was 19.31 million tons. The countries being the main wood pellets consumers were the United Kingdom (UK) (9.4 million tons), Italy (3.4 million tons), Denmark (2.9 million tons), Germany (2.3 million tons), and Netherlands with 2.2 million tons respectively [15]. These five countries are between the top 10 importer countries of wood pellets in the world [20]. However, the main importer in the Europe is the UK. Consumption in the UK increased in 2018, reaching around 8.5 million tons with a

significant part of this growth due to the conversion of the fourth unit of Drax and additional power plants converted and put online to biomass (e.g. Czech utility EPH's Lynemouth; MGT Power's Teesside) [16, 21].

Many authors have pointed out that United States of America is the biggest exporter of wood pellets in the world and second biggest producer after China, which in 2018 produced 20.25 million metric tons of wood pellets and the USA 8.2 million metric tons [22]. According to Biomass Magazine in 2020 the USA exported 7.26 million metric tons of wood pellets to the EU and the UK was the major buyer for U.S. wood pellet exports with 5.63 million metric tons [23]. The UK has a prominent role in wood pellets imports from the USA, however, the UK has left the EU, but it has their sustainability requirements to import this product for energy production and it is of relevant importance since the UK does not have the capacity to produce their own wood pellets.

The main reason why the USA wood pellets industry developed is the high demand from the EU [24, 25, 26]. Since 2007, the Southeast region of the USA timber output is close to 60 percent of all timber produced in the United States, and it shows its comparative advantage in growing timber and a new product mix that favors smaller diameter trees, and forest residues. The USA Southeast region is the most productive timber producing in the country [27]. This is shown because the volume of growing stock grew by more than 75 percent while industrial output of wood products more than doubled over the last half of the twentieth century [28], and because Southern forests, have the highest amount of planted area in the USA with 71 percent of all planted timberland [29]. In addition, The US Southeast timberland has remained stable and has increased in 3 percent from 1953 to 2015, and the forest growth has outpaced removals by 38%, its forest inventory increased by 147 percent from 142.1 to 296.1 billion cubic feet in the same period [27].

Because of the industrial capacity installed in the USA South and being this region a big supplier of wood to the lumber, pulp, and paper industries, there is a big amount of forest residues for wood pellet production. This situation has been favorable for the forest industry to establish the bulk of the industrial wood pellet manufacturing capacity in the USA states of the Atlantic and Gulf coasts [25, 30], together with strategic characteristics such as proximity to EU markets and the availability of biomass resources, labor, infrastructure and industrial experience [29]. Currently the USA Southeast has 73 percent of the manufacturer capacity representing close to 62 percent of wood pellet industry employment in the USA [31].

The European Union is the main market for wood pellets, of which 81% is currently met by the European pellet industry, however the gap between European production and consumption has grown to more than 8-fold [32]. For this reason several authors have pointed out that the wood pellets exports from the US to the EU will continue at least for the next 10 years [24, 28, 32–34]. However, the EU society, and USA and EU environmental groups have concerns related to forest sustainability in the long term for the use of forest biomass for wood pellets production that are imported into the EU. The European Commission proposed implementing standards for sustainability of

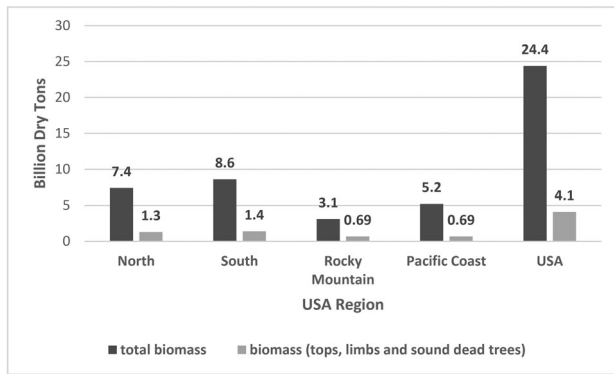


Figure 1. USA total biomass aboveground, and tops, limb and sound dead trees on timberland in the United States by region (includes live trees greater than 5-inches diameter breast height). Data source [29].

wood pellets consumed in the EU. Forest management laws and regulations in the USA directs land management agencies to conduct forest assessments at 10 years periods and updated at 5-year periods in order to address the detected sustainability issues identified on those assessments. The federal government supports sustainable forest management by providing technical assistance and financial and tax incentives to private landowners. Monitoring of natural resources and reporting their dynamics through time is assessed and projected using modeling to support decision making to assure that sustainable forest management is achieved.

The main objective of this paper is to conduct a review of the literature published from 2010 to March 2020 that assesses the use of residual biomass sources in the United States of America and focused on the Southeast region where the main wood pellets production for exports to the European Union takes place from 2020 to 2050. This article will help to understand the dynamics of the of forest biomass supply for wood pellets production in the USA to be exported to the EU and the UK.

United States of America southeast forest resources

The United States has maintained an almost constant amount of forest and woodland area of 823 million acres for the past one hundred years. Currently forest land area occupies 766 million acres with 67% of it legally available for harvest activities; tree cutting, and removal occurs on less than 2% of forest land per year. More area is affected by natural disturbances like insects, disease, and fire affecting close to 3% of the forest land area annually [29].

The U.S. wood pellet production for export to the EU and the UK occurs in the Southeast. It includes 13 states in the Southeastern and South-Central subregions. The area extends from Virginia south and west along the Atlantic and Gulf coastlines to Texas and includes the interior states of Arkansas, Kentucky, Oklahoma, and Tennessee. The region has diverse climatic and soil conditions that correspond to its varied physiography [35]. In the South total forest land is 245.5 million acres - equivalent to 46% of the South's land area.

Southern forests have the highest amount of forest plantations with 48.08 million acres planted corresponding to 71% of all planted timberland planted in the U.S. (67.44 million acres). The main combination of planted tree

species on southern timberland is loblolly-shortleaf pine. Another combination of pine trees is the longleaf and slash pines which represent 14% of the region's plantations. Loblolly, shortleaf, longleaf, and slash pine trees, called "yellow pines" in the region, are used in the main forest industries [29].

Forest inventory results indicate that southern yellow pine plantations occupy 18% of the forest area corresponding to 47% of the softwood volume in the south region. In general forest plantations represent 67% of the annual growth of softwoods and account for 82% of the annual removals of softwood species in the south region. In the South natural pine stands have lower productivity per acre than southern-yellow pine plantations. Natural stands have more diverse species composition with more hardwood species and have a greater proportion of their trees in larger diameter classes. The growth-to-volume ratio per year for planted stands is 10% of the standing volume, and in natural stands this growth-to-volume ratio is 3% (seven times less than planted stands). Removals to volume ratio for planted stands is 7%, showing that for every 100 cubic feet (cft) of live tree volume 7 cft of volume is removed per year, in natural stands this removals to volume ratio is 1%. Southern pine plantations have higher annual growth and have more volume removed of live trees per acre and have higher standing volume than natural pine stands [29].

In the same region natural stands are dominated by hardwood species. Natural stands cover 79% of the hardwood volume and 67% of all live regional average annual growth. The main species of hardwoods in the region are oak and hickory with 48% of the total hardwood area in natural stands. Woodland hardwoods follow with 13% of the South's hardwood forest area [29].

The total live-tree volume on the US timberland exceeds 1 trillion cft - equivalent almost to 9 billion stacked cords of wood. The U.S. forest industry covers 17% of global roundwood production, and it has the highest intensity of industrial roundwood consumption per capita. Wood energy¹ in 2016 accounted for nearly 20% of all renewable energy and 41% of all bioenergy produced in the country. The US accounts for 26% of total wood pellet production worldwide [29].

The total standing volume for all timber in the Southern region is 398.61 billion cft, with a total standing volume of 129.15 billion cft softwoods and 269.23 billion cft of hardwoods. The softwood growing stock on timberland is 8.85 billion cft per year and for hardwood 6.18 billion cft per year. Net growth for all species in timberland in the South is 15.05 billion cft per year [29].

Timberland annual removal of growing stock in the South is 5.64 billion cft of softwood and 2.2 billion cft of hardwood for a total of 7.85 billion cft, and removals from other sources are 2 billion cft, totaling 9.88 billion cft of roundwood products, logging residues, and other removals from growing stock and other sources [29]. The U.S. total timberland annual removal of growing stock is 18.22 billion cft with 11.54 billion cft from softwoods equivalent to 63% of the total annual removal in the U.S. The South's annual removal of growing stock is equivalent to 54% of the total U.S. annual removal [29].

Removals and mortality of growing stock on timberland in the South (without removals from other sources)

account for 10.78 billion cft, which is 2.85% of the total volume, and 78.3% of the total annual net growth of the timberland in the South [29].

Total live biomass above ground of live trees greater than 5 inches diameter breast height in the South is 10.21 billion dry tons, which are 31.6% of the total live biomass in the US. The total biomass aboveground, and tops, limb and sound dead trees on timberland in the United States by region is showed in Figure 1. Logging residues in the South are 2.05 billion cft with almost 50% each of softwood and hardwood. These logging residues are close to 55% of the total amount in the US [29].

One indicator of sustainable forest management is the wood growth to removal ratio. According to Jefferies and Leslie [27] this ratio can indicate how much wood removal exceeds wood growth, and it is obtained by dividing the amount of growth between the amount removed. When the result is bigger than 1.0 it indicates that growth exceeds removal at that moment for that period of time and that area. In the southern U.S. this ratio has had values between 1.02 and 1.66 on a total basis. However, these authors pointed out that growth has exceeded removals by 32% on average indicating that in the South forests have grown more that they have been harvested [29].

Growing demand for wood pellets in the EU

The main cause of EU demand for wood pellets resides in the European Commission's 2020 climate and energy package, binding legislation passed in 2009 that mandates the EU's 20-20-20 targets [27, 36]. These targets have three individual goals for 2020: 1) Reduce by 20% EU greenhouse gas emissions from 1990 levels [37, 38] Increase the renewable portion of EU energy consumption to 20% [14], and 3) Improve by 20% EU energy efficiency [39].

The EU indicates that the Renewable Energy Directive (RED) is the legal framework for the advancement of renewable energy across all sectors of the EU economy. It provides a set of common principles and rules to eliminate barriers, encourage investments and create cost reductions in renewable energy technologies, and allows citizens, consumers and businesses to participate in the clean energy transformation. On July 2021, the RED was amended by the reorganization of the Renewable Energy Directive (EU) 2018/2001 (REDII), which provides the framework for the promotion of renewable energy in the European Union from 2021 to 2030. The REDII sets an overall binding renewable energy target of at least 32% by 2030 with a 14% target for the transportation sector, and a clause for a possible upward revision by 2023 [40]. Several EU states are using wood pellets to co-fire² plants replacing coal for electricity generation and heating to meet their targets. Because of this the EU demand for pellets has currently exceeded its domestic production and this situation has increased imports of wood pellets from the U.S.

Several authors have been intensively studying wood pellet markets for the last 10 years and their main findings indicate that EU demand will increase at least until 2050. The studies have been done using many scenarios with different combinations of factors affecting the demand and production of wood pellets. Rafal *et al.* [38] studied the effects of EU biomass imports from the Southeast U.S. on

timber prices, inventories and production and on EU imports of feedstock from Southeast U.S. using the sub-regional timber supply model in a projection period from 2008 to 2038. They found that under the scenario of low EU pellet demand, the impacts of woody biomass from US forests will not have extreme effects on timber markets and could stimulate carbon storage and establishment of forest plantations. Although, in a scenario where the EU pellet import demand is increased under a more aggressive U.S. renewable energy policy, they concluded that there would be a considerable increase in timber prices which wouldn't be economically sustainable for the forest industry in the Southeast. Kittler *et al.* [41] indicated that wood pellet market experts appear to agree that European demand for wood pellets in 2025 is expected to be limited to 20-22 million metric tons, of which 10-12 million tons is expected to be sourced from the U.S. According to this report, this amount of supply from the U.S. could represent close to 20% of the pulpwood used for paper production in the Southeast in 2015, or the intensive harvest of a volume of the total growing stock on 169 thousand hectares per year of pine plantations, or the extensive harvest of small and medium sized trees on 550,000 hectares per year of pine plantations. Aguilar *et al.* [42] estimated that in 2018, the EU demand for wood pellets was close to 23 million metric tons, of which the U.S. supplied 27%. Kline *et al.* [43] indicated that all biomass residues used for bio-energy in the U.S. represent about 6% of the 363.3 million green tons of total removals in 2018 in the Southeastern U.S. and estimated that pellets make up 27% of the total industrial fuelwood uses in 2018, which is consistent with the findings from other authors [42]. According to Kittler, Stupak and Smith [24], it is highly probable that wood pellets imported from the Southeast U.S. in the next decade will comprise the largest source of energy biomass other than those generated within the EU even if European demands are currently predicted to stagnate.

This situation indicates that based on the current European Community targets for renewable energy, and member state incentives, EU demand and consumption will continue to grow. However, EU production is not expected to be able to keep up with this demand. Under these circumstances the United States has the potential to supply at least half of the EU imports if trade flows remain as they are at the present moment [44]. The EU produces nearly 30% of world wood pellet production and its demand represents nearly 50% of the global market [21].

U.S. wood pellets production capacity

Wood pellets in the U.S. are mostly manufactured from forest residues or low-grade, low-quality logging and saw mill byproducts [24] that would otherwise go to waste (i.e. tree tops and limbs, thinning treatments, mill residues such as sawdust or bark, low-quality wood). Most of the production and exported wood pellets come from Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia [38]. In 2020 the U.S. exported 7.2 million metric tons of wood pellets [23]. Wood pellets are produced with forest and mill residues from thousands of small privately-owned forests in those states. For such landowners,

environmental protection laws, the existence of federal assistance programs, state rules and regulations, and the implementation of Best Management Practices (BMPs) provide reasonable assurance of sustainable forest management. Adoption of BMPs by these small landowners is estimated at nearly 92% [45]. The raw material known as harvest or logging slash made up of the top, limbs, pine needles, pine cones and bark [46, 47] serves to accomplish the BMPs. Landowners are required to leave close to 30% of this logging slash on the forest floor [48] with the aim of decreasing hazardous fuels and risk of harmful insects and disease, protecting air quality by decreasing the risk of wildfire, improving access to forage for grazing and browsing animals, and other aims such as improving soil organic matter as recommended by the Natural Resource Conservation Service [49]. The amount of wood chips, residuals, and wood fuels harvested in the U.S. in 2018 was 84.81 million cubic meters representing 19.33% of the total amount of timber harvested [48]. The amount of residues in wood processing mills in 2016 in the USA were 63.7 million dry tons, from this amount 46 percent was used for fuel and for fiber products 38 percent [29]. Table 1. Shows the amount of million m³ of wood residues produced in the main wood pellets exporter countries in the world in the last 13 years.

Wood pellet mills in the Southeast U.S. started operations in 2008, filling a void left by the closing of non-pellet mills like the closing of pulp and paper mills. In that same year there were two wood pellet mills exporting to the EU; one in Florida and another in Georgia [50]. Since 2008, U.S. export capacity increased from less than 100,000 tons to almost 2 million tons in 2011 [51], reaching 3.89 million tons in 2014 [41], 4.6 million metric tons in 2015 [52], 6.9 million tons in 2016 [53], 7.3 million tons in 2017, 9.0 million tons in 2019 [42], and dropped to 7.2 million tons in 2020 [23].

The production capacity in the U.S. has continued to grow. In June 2021 there were 79 wood pellet plants in the U.S. with a total annual production capacity of 12.8 million tons; 1.47 million tons of green feedstock were used including roundwood/pulpwood (15.3%), sawmill residuals (33.8%), wood product manufacturing residuals (6.1%), and other residuals (44.8%) to produce 770 thousand tons of wood pellets. The biggest amount of wood pellets (81.8%) came from 33 facilities in Southeast U.S. [54].

According to Forisk Consulting [55] wood pellet production capacity in North America has increased 144% over the past decade. Growing to meet European demand for renewable energy—and more recently demand from Asia—wood pellet manufacturing capacity has consolidated and shifted across regions. In 2019, the U.S. South was the largest wood pellet producing region in North America. With 11.5 million tons of capacity, the region accounted for 58% of North America's wood pellet capacity. The South's production capacity has increased more than fivefold since 2009, growing at a compound annual rate of 14%. Since 2009, the average capacity of wood pellet manufacturing facilities in the U.S. South grew 180%.

Parish *et al.* [34] indicated that wood pellets trade with the EU is influenced by the wood pellets high quality characteristics specified by approved standards. They also pointed out that although the EU can get wood pellets

from near countries the high quality of USA wood pellets and their relatively lower cost of sea transportation relative to land makes the USA wood pellets more attractive for importation. The quality of densified biomass application as a solid fuel produced using pellet mill and briquette press systems has been evaluated in the USA by the Pellet Fuel Institute and in Europe by the Common European Standard (EN) with the existing international standards developed for both systems [12]. Originally designed by the Deutsches Pelletinstitut as, ENplus, this certification system ensures the quality of wood pellets over the entire supply chain (i.e. from production to end-user delivery). This certification scheme is governed and managed by the European Pellet Council with support from National Associations, managing the certification on a national level. Currently it covers 46 countries with a total volume of 12.4 million tons of certified pellets produced in 2020 and 14.2 million tons projected in 2021 [15].

The UK standard, which became mandatory in April 2015, includes a set of principles for using risk assessments, regional sustainability monitoring, reporting, and compliance with local laws and regulations to assess sustainability, when purchasing timber and wood products, including wood fuel. The principles are based on social, economic and environmental practices that are part of sustainable forest management based on approved international criteria. It also includes a requirement for evidence demonstrating that the biomass comes from legal and sustainable sources with demonstrated chain of custody from the forest source to the end [56, 57].

Major consumers of wood pellets within the EU are the UK, Italy, Denmark, Germany, Sweden, France, and Austria, but the United Kingdom (UK) is by far the largest market accounting for 82% in 2017. Wood pellet growth in the UK is associated with the conversion of large-scale coal-fired units to biomass. Import totals by other top EU member state markets have been fluctuating in large part due to policy uncertainty, the warm winter, or consumption outpacing production [21].

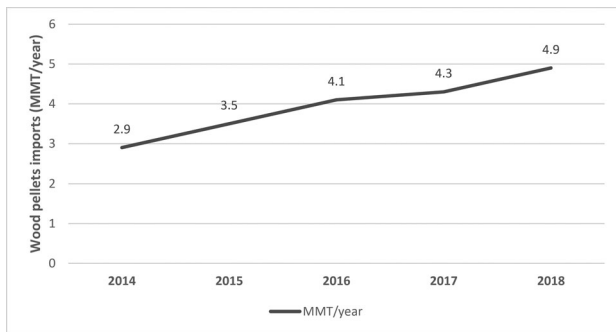
In 2017, 80% of U.S. wood pellet exports went to the United Kingdom [25]. Actual exports to the UK were down slightly, but volumes to Denmark and Belgium increased 293% and 76%, respectively. The U.S. exported 50,000 tons to the Italian heating market in 2017 after a 30-month hiatus due to weak pricing and the strong US dollar. A bulk shipment of pellets went to the Netherlands in October as co-firing activity resumed in the Dutch market [58]. In 2018 91% of US wood pellet exports went to the UK (Figure 2).

Growth in the EU and UK in the demand for industrial wood pellets, under current policy, is expected to plateau in 2022 at about 20.3 million tons per year. However, growth in the northeast Asian markets is expected to continue well into the 2020s (Future Metrics, 2019, cited by [16]).

Forisk [59] indicated that US wood pellet exports increased 14% in 2019. The UK remained the largest importer of US wood pellets with 78% of total US volumes. The UK imported 5.33 million metric tons of wood pellets from the US, a 13% year-over-year increase. Export volumes to the UK are expected to continue to rise with the completion of MGT Power's 299 MW CHP facility. Through February 2020, U.S. wood pellet exports were up 18%

Table 1. Wood residues (million m³) produced in the main wood pellets exporter countries in the world in the last 13 years. Source [20].

Country	Year												
	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Austria	3.14	3.16	2.84	2.96	2.70	2.72	2.57	2.65	3.05	3.02	3.26	3.40	3.37
Canada	8.77	8.77	8.77	8.77	8.77	8.77	8.77	8.77	8.77	8.77	8.77	8.77	8.77
France	8.29	7.33	7.89	13.34	16.36	20.27	20.12	19.92	7.66	8.37	8.22	7.16	8.18
Germany	0.82	2.43	2.83	3.10	2.99	3.29	3.24	3.67	3.58	3.88	4.32	3.91	4.40
Latvia	2.12	0.89	1.16	0.34	0.51	0.57	0.66	1.54	1.54	1.65	1.65	0.83	0.38
Sweden	5.00	5.00	5.00	4.00	4.15	8.36	8.60	10.17	8.79	9.15	9.48	9.40	9.30
USA	15.40	9.70	11.75	11.65	12.32	13.19	13.80	13.80	13.80	14.27	14.81	15.28	13.24

**Figure 2.** United Kingdom wood pellets imports from the US (MMT/year). Data sources [22, 37].

year-over-year, driven by demand from the UK and Belgium [59].

On November 2019 Drax Group released a trading statement announcing company plans to have 5 million metric tons (MMT) of annual pellet capacity in place by 2027. The increased capacity is expected to help reduce biomass costs [60]. In December 2019 Enviva received approval in Alabama to establish a new plant with planned permitted capacity expected to be 1.15 MMT. The plant would initially be constructed to produce 700,000 metric tons of wood pellets per year. The facility could be expanded to 1.15 MMT of production capacity in the future [60].

In 2021 the U.S. current installed capacity for wood pellets production is 14.64 MMT/year with 122 operational wood pellet plants [23], although, Brandeis *et al.* [61] indicated that current capacity for pellet production in the U.S. South is 22.7 million green metric tons of wood input, with 62% of that wood input coming directly from the forest. Mill residues make up only 38% of current expected feedstocks; softwood is expected to continue to dominate the feedstocks.

World wood pellet production has been increasing. From 2017 to 2018 it grew 14%. In addition, production in Asia has been expanding where volume has increased by 54% in 2018 in Vietnam, Malaysia, and Thailand [16].

The World Energy Council [62] indicated that EU wood pellet production in 2014 was 13.5 million tons, and the consumption was 19 million tons; the difference was imported mostly from the U.S. In 2016 the EU manufactured more than 50% of the global wood pellets production (29 million tons).

This growth of the wood pellet industry is a result of increased EU imports from the U.S. In 2020, U.S. wood pellet exports were up 379% from 2012 (Figure 3). In 2020, U.S. exports to the EU totaled 7.2 MMT, representing a value of \$981 million. If EU demand and trade flows remain consistent with current patterns, the United States has the potential to supply 65% of the import demand [44].

In 2016 the EU consumed 23 million tons, with 66.5% consumed by Italy, Germany, Denmark, Sweden and Italy, this last being the highest consumer with 32.6%. This high consumption of wood pellets in the UK and Italy relies on imports with the UK importing 94.7% and Italy importing 81% of their consumption [7]. The Foreign Agricultural Service [21] indicated that in the EU, 59% of the renewable energy consumed is generated by bioenergy. Of this, 70% is contributed by solid biomass, 12% by biogas, 11% by liquid biofuels, and 7% by municipal waste. The EU is the world's largest wood pellet market, with a consumption of roughly 29.1 MMT of pellets in 2019. Based on European Community mandates and EU Member State incentives, demand is expected to further expand to about 30.8 MMT in 2020. Future consumption will significantly depend on a range of market factors and EU Member State incentives and conditions.

The behavior of European Union wood pellet consumption and imports, and U.S. exports for the last 10 years is presented in Figure 4. This figure shows that the US in 2011 covered 64% of the EU imports and 16% of the EU consumption, while in 2020 the US covered 58% of the EU imports and 23% of the total consumption of wood pellets. The United States is the EU's leading supplier, and its share of the EU wood pellet market has continued to increase. U.S. market share reached 58% in 2020, an increase of 350% from 2011 (Figure 4).

According to Forisk [63] based on project and sector analysis, growth in global demand for industrial wood pellets is expected through 2025, growing at a compound annual rate of 7% and reaching 31 million metric tons before declining. The largest projected increases are expected in Asia, with demand for industrial wood pellets in South Korea and Japan projected to advance 19%, approaching 13.4 million metric tons by 2025. Forisk [63] pointed out that even with these increases, Europe will continue to be the main industrial wood pellet market up to 2026 followed by a decline in European demand when European subsidies expire starting in 2027.

Forisk [33] analysis suggests that woody biomass use for bioenergy projects in the U.S. could reach 83 million tons per year by 2030. These projections are consistent with those from Cocchi *et al.* [64] who projected an increase in total forest and wood waste resources for wood pellet production from 74 million dry tons in 2012 to 79 million dry tons in 2030 at a price of \$40 per dry ton, without considering federal lands production. However, when prices increase to \$50/dry ton, this range goes from 85 to 90 million dry tons, and with a price of \$60/dry ton the supply range increases from 90 to 95 million dry tons for the same periods. In 2020, U.S. wood pellet export volumes increased 4.9% while Canadian wood pellet exports rose

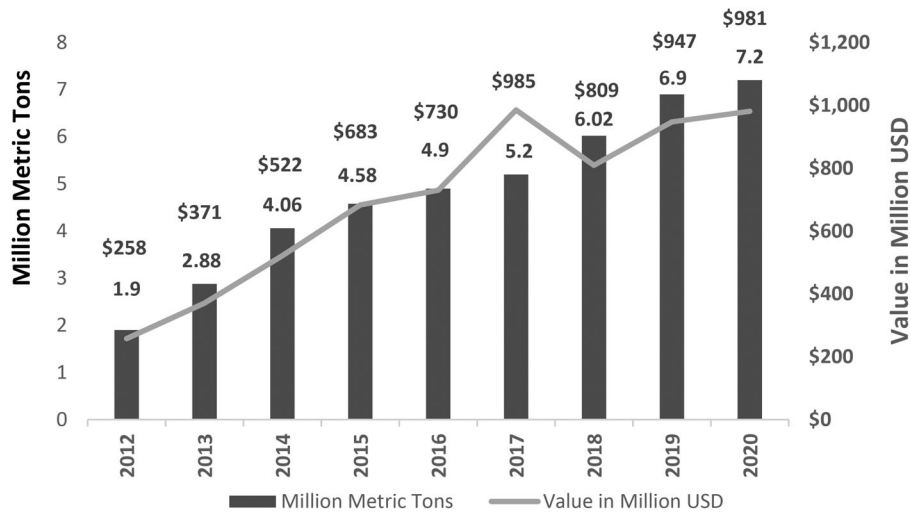


Figure 3. U.S. Wood pellets exports 2012 -2020. Data source [21].

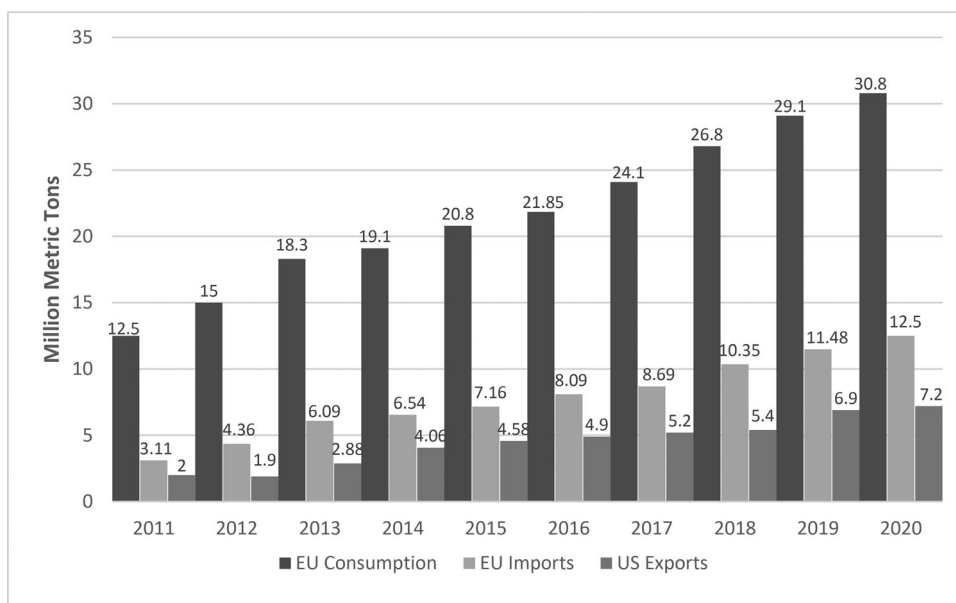


Figure 4. European Union wood pellets consumption and imports, and United States exports. Data sources [21, 25].

11%. North American wood pellet capacity is expected to increase 15% in 2021 [33].

Future demand, potential risks, opportunities, and barriers to increase imported biomass

Future demand impacts in southeast forests

Several authors have studied the capacity and impacts of increased wood pellet demand and the changes in timberland management and area in the U.S. One of those studies was conducted by Alig and Butler [65] through empirical modeling that projected US forest cover type changes up to 2050. They found out for industrial lands that by 2050 forest cover types will decrease by 8.6 million acres (38%). The main two cover types impacted by this decrease are upland hardwoods (3.4 million acres) and natural pine stands (2 million acres). This decrease of cover types is modeled to be caused by a shifting to pine plantations, which were projected to increase by 53% representing almost 17 million acres at the end of the projected time. Hardwood forests in 2050 were projected to cover about 50% of the southern private timberland area,

which will be twice the amount for planted pine in the region. Another projected impact is the loss of 3 million acres of forest cover (from 201 million acres in 1997 to 198 million acres in 2050), due to deforestation for urban and development uses. The area of natural pine on private lands is projected to remain constant. Wear and Greis [28] modeled scenarios for the South’s forests based on a range of effects from urbanization, bioenergy, climate change, land ownership changes, and invasive species using as a baselines 1997, and 2010 with projections until 2060. Their findings are consistent with those from Alig and Butler [65] for deforestation from urban development, however the impacts are higher, because in their study the South is forecasted to lose between 11 million acres (7%) to 23 million acres (13%) of forests, nearly all to urban uses for the projection period.

Wear and Greis [28], using 2010 as baseline regarding planted pine, forecasted an increase of 28.2 million acres in 2060 under a modelled scenario of relatively high level of urbanization, high timber prices and high planting rates. Alternatively, under a scenario of low urbanization, low timber prices and low planting rates the planted pine area will only increase by 7.8 million acres. This study also indicates

that forecast losses in natural pine forest types mirror the gains in planted pine forests and are therefore related, albeit inversely. Abt *et al.* [66] applied the Subregional Timber Supply model in a simulation of timber markets where increases in demand for timber from the U.S. Coastal South derived from both pellets and other bioenergy demand, with a baseline of 2010 and projections up to 2040. They found out that increased pine harvest promoted increased investments in forest plantations resulting in higher inventory levels than under the baseline; also timberland area increases with increases of raw material for pellets, because of the establishment of forest plantations on marginal agricultural lands.

Duden *et al.* [67] also had consistent findings with results from Alig and Butler [65], Wear and Greis [28] and Abt *et al.* [66], when they modeled the impacts on land use dynamics in the US South regarding the increase of forest plantations establishment. Their results showed an increase in wood pellet demand between 2010–2030 causing an increase in pine plantations establishment from 4.7% to 11.2% using scenarios of high and low housing demand. Alternatively, Costanza *et al.* [68] simulated landscape change from 2010 to 2050 under five scenarios of woody biomass production for wood pellets and liquid biofuels in North Carolina, U.S. They indicated that including harvest of conventional forest biomass, but not the conversion of marginal forest lands, led to more total forest area in 2050 compared with the baseline of 2010, but the loss of important habitats in the longleaf pine and bottomland hardwood ecosystems generally occurred under those five scenarios.

With reference to forest inventories for wood pellets production Wear and Greis [28], Abt *et al.* (2014), and Galik and Abt [69] in their different projections for the long-term supply of woody biomass for wood pellets found an increase in removals, increase in forest area, and little change in forest inventories. Specific estimations were provided by Wear and Greis [28], indicating that total growing stock volumes are forecast to change in response to land use change and different intensities of timber harvesting. In all scenarios, pine growing stock inventories increase. In the low urbanization/low-timber-price scenario, softwood inventories increase 22% (37 billion cft). The smallest increase is 15% (18 billion cft) for the high-urbanization/high-timber prices scenario. Hardwood growing stock inventories had a different behavior. In 2010 there were 171 billion cft hardwood growing stock volumes, which will peak between 2020 and 2040 for all scenarios, and then decline into the year 2060. They also pointed out that while woody biomass harvest is expected to increase with higher prices, forest inventories would not necessarily decline because of increased plantations with fast-growing species, conversion of non-forest lands to forest plantations, and intensive management of forest land.

According to Kline *et al.* [43] the Southern U.S. pellet supply chain presents an opportunity for transition to low-carbon industries and innovations promoting better resource management and helping to displace coal for energy in Europe and contributing to the Sustainable Development Goals by providing reasonably priced clean energy, creating jobs, and economic growth among other benefits.

Potential biomass supply from US southeast forests

Several authors have provided a range of different futures or scenarios for the US South's forests considering different factors influencing future wood pellet demand such as growth of population, urbanization, use of bioenergy, climate change, land ownership changes, movement of invasive species, sustainability guidelines, and environmental impact modeling in different combinations from 2010 to 2050, with different periods in the middle (2030 and 2040).

Cocchi *et al.* [64] projected that the US Southeast raw material for wood pellet production could be from 74 million dry tons in 2012 to 79 million dry tons in 2030. These projections do not consider the raw material from federal lands, and they pointed out that when prices increased to \$50/dry ton, this range goes from 85 to 90 million dry tons, and with a price of \$60/dry ton supply increases from 90 to 95 million dry tons. Duden *et al.* [67] provided more conservative projections with a baseline of about 0.5 million tons in 2010; their results projected an additional demand for wood pellets of 11.6 million tons in 2030. Forisk [33] indicated that the U.S. wood pellet production increased 4% in 2020 and projects that by 2030 U.S. wood use for bioenergy could reach 83 million tons per year. Other projections using 2010 demand as the baseline showed 44 million green tons of biomass production with a pellet production of 32.2 million tons for 2040 [66]. However, Wear and Greis [28] indicated that US Southeast harvesting of woody biomass for use as bioenergy is projected to range from 170 million for low consumption to 336 million green tons by 2050 for high scenario adding in both cases urban wood waste, an increase of 54 to 113% over 2013 levels. Finally, from all these studies, the main finding is that the US Southeast forests could be able an important source to supply woody biomass for wood pellet production to cover some level of the EU demand for the next 40 years taking into consideration the tendencies of the increased demand of wood pellets.

Potential risks, challenges, opportunities and research needs

a. Risks

Based on these studies, it is possible to identify common results from all of them, and the different futures or scenarios for the US South's forests until 2060 and intermediate periods. These studies indicated that expansion of urban and development uses are the reason that Southern timberland area is projected to decline in different intensities. The biggest estimates are from 1997 to 2060, with a forecast to lose between 11 million acres (7%) to 23 million acres (13%) of forests, nearly all due to a change to urban uses. Another common finding is that the entire South is expected to lose at least some forest acreage under all evaluated futures, but strong timber markets can ameliorate losses of southern forest somewhat, but this comes at the expense of cropland uses [28].

Most of the authors also pointed out that the hardwood forests are projected to cover about one-half of the southern private timberland base, twice the amount for planted pine in the region, and that the private area in pine plantations is projected to increase in different percentages. For

example, by 2050 an approximate 53% increase largely owing to the addition of pine plantations on forest industry lands [65] or by 2060 planted pine is forecast to comprise somewhere between 24 and 36% of forest area [28]. In general, it can be indicated that all authors pointed out that timberland area increases with an increase in demand for feedstock for pellets as more plantations are established. An indication of this situation is that since 1997, forest land has increased in all but one region. The largest increase has been in the South, at 6% [29].

Other common findings are an increase in removals and forest inventory, with the expectation for prices remaining high or continuing to increase. Regarding environmental impacts, the studies indicated in general that the forest carbon pool in 2060 would be smaller than in 2010 because net biomass growth gains on forested lands are offset by the loss of forested land caused by urbanization.

Wear and Greis [28] indicated that forecasts of human population growth and urban expansion raise the possibility of substantial impact on terrestrial wildlife species and the communities that support them over the next several decades, and the number of species negatively affected by the loss of forest is expected to increase. The geographic pattern of richness and imperilment indicates that many species in the South are clustered into identifiable areas of unique richness. The recommendation is that the analysis of the overlap of these areas with hot spots of imperiled species under the projections of urban growth and associated forest loss suggests that several subregions may experience conflicts between development and species conservation and management. They also indicated that climate change represents an additional source of stress for biodiversity on terrestrial species and ecosystems. Climate scenarios projections for temperature increase and variability in precipitation patterns over the next century may change the future distribution of many wildlife and plant species. Dwivedi et al. [70] also indicated that the main drawbacks are associated with potential impacts on air, water, and biodiversity that arise if the resource base and harvest activities are improperly managed.

Another drawback is pointed out by Nepal et al. [71], regarding a situation where the use of logging residues is restricted because it is too costly, because future environmental restrictions do not allow their recovery, or because its biophysical availability is limited. Under such conditions, their results suggested that increasing consumption of wood biomass feedstock can be met by supplies of pulpwood, resulting in greater competition for pulpwood between energy and traditional wood products. This finding implies that the wood pulp, paper, and panel industry—especially in the US South—might need to compete for increasingly expensive raw material (up to 42% higher pulpwood prices) under higher wood energy demand and restricted logging residue use.

Challenges

Goetzl [72] indicated that the European wood pellet buyers through the Sustainable Biomass Partnership (SBP) will make it easier for EU pellet purchasers to demonstrate compliance with regulations, but rigorous criteria on sourcing of wood raw material will be challenging for wood

pellet producers. Some proposals, including the proposed sustainability rules in the UK, favor wood material obtained from forests certified under a recognized forest certification program. This poses a potential problem for U.S. producers since most of the wood used in U.S. pellet manufacturing derives from family forest owners that do not participate in a certification program. Ultimately, the various requirements related to the sustainability of wood resources may affect the competitiveness of different wood pellet suppliers and their access to EU or other markets. Concerns about the carbon neutrality of using wood energy may also shape future policies that affect biomass energy and wood pellet demand.

Aguilar et al. [42] found positive trends in timberland conditions; however they recommended continued monitoring of localized impacts of wood pellet mill operations taking into consideration population changes, expansion in wood fiber demand from other competing sectors, and extreme weather, while also controlling for overall forest ecological region conditions.

Brandeis et al. [61] also pointed out that environmental groups and scientists have raised concerns over the sustainability of forest resources in the U.S. South under the current capacity for pellet production, and additional capacity from announcements has exacerbated these concerns.

Opportunities

Studying the status and future situation of using wood pellets from Southeast U.S. for renewable energy Dale et al. [30] found that wood pellet production levels of 2017 had a benign outcome on forest ecosystem services. They also pointed out the potential benefits of future production if landowners keep the forests when wood pellet production becomes more efficiently integrated into proactive forest management plans, and regulatory and voluntary provisions exist to protect forests. They recommended research, monitoring, and evaluation of managed forests to assess that forest management and its outcomes are achieved and generate recommendations for improving forest management and informing decision making in the U.S and the EU.

Fernholz, et al. [73] pointed out that markets for biomass do not provide enough financial incentive to support harvests of large mature, high-value trees. Biomass markets can support improved forest sustainability by utilizing low-value materials and reducing waste in processing. Economics preclude the use of old-growth or large mature trees in the context of harvesting for bioenergy production and additional environmental and social conditions exist to protect these forest values. In their review, they concluded that strong markets for forest products, including biomass markets, can support keeping forests as forests and contribute to diverse goals for forest health and resiliency.

Dwivedi et al. [70] concluded that the use of imported wood pellets from the Southern United States for electricity generation in The Netherlands saves considerable greenhouse gas emissions when compared to fossil-based energy sources like natural gas, oil, and coal. In their analysis of timberland conditions within wood pellet industry procurement landscapes of the eastern US Aguilar et al. [42] showed upward and downward associations. On the

one hand, operation of wood pellet manufacturing in the US coastal southeast showed no significant changes in Carbon (C) pools of live nor standing-dead trees, and a concentration of live C in fewer growing-stock trees. Procurement areas of large-scale manufacturing facilities had higher levels of C in live trees. Moreover, a greater overlap of wood pellet mills' procurement areas exhibited discernible increases of selected C pools. A similar benefit was concluded by Kline *et al* [43] who found out that production of wood pellets in the SE US and shipments to displace coal for energy in Europe generate positive effects and strengthen the wood pellet supply chain in the region providing employment in depressed rural areas and contributing to the displacement of fossil fuels. They concluded that the SE US wood pellet supply chain provides an opportunity for transition to low-carbon industries and innovations while incentivizing better resource management.

Brandeis *et al.* [61] indicated that the use of U.S. timber to produce wood pellets for nondomestic utility consumption is a still growing wood products sector in the U.S. South, and there is competition among domestic pulp producers for these feedstocks. Such competition has the potential opportunity to increase or provide a floor against decreasing timber prices, thus improving the probability that landowners will keep their land in timber.

Finally, Parish *et al.* [34] studied the transatlantic wood pellet trade using the telecoupling framework, which, according to Liu *et al.* [74], is an integrated concept to incorporate both socioeconomic and environmental interactions among coupled human and natural systems over distances. In this study Parish *et al.* [3] concluded that the trade of wood pellets between the US and the EU is an example of a mutually beneficial telecoupled system with the potential to provide environmental as well as socioeconomic benefits to both parties. They also recommended monitoring of the Southeast U.S. forests to determine if potential environmental and socioeconomic impacts of the wood pellet trade such as impacts on biodiversity and endangered species, loss of ecosystem services, changes in forest composition and growth of green economy jobs among others occur in the future.

Conclusions and research needs

From this review, it can be concluded that the majority of forest biomass assessments projections showed that forest biomass from the Southeast of the USA for wood pellets production in 2030 could vary from 74 million dry tons up to 95 million dry tons depending on the increment on prices per dry ton, and for 2050 could range from 85 for low consumption scenario to 162 million dry tons for high consumption scenario using a conversion factor of 2 green tons per one ton of wood pellets. These levels of forest biomass supply will allow to cover the European Union and United Kingdom demand for the next 40 years taking into consideration the current and projected tendencies of the increased demand of wood pellets.

Most of the research needs identified in this review are related to topics such as the long term monitoring of sustainable forest management impacts on biodiversity, fragile ecosystems, carbon pools, ecosystems services and forest productivity of natural forests and forest plantations; techno-economic analysis of wood pellets production for

different supply chains as technology and societal values are changing; calibration of the future trends for supply assessments using the data when the prognosis time has been reached to estimate the next period of future trends; assessment of the economic and environmental impacts of policy wood supply for wood pellets production on forest owners in rural communities, and focus on future climate change impacts on sustainability concerns of forest biomass use for wood pellets production.

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Disclosure statement

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