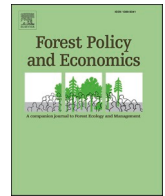




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Forest sector models for tropical countries - A case study of Colombia

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A B S T R A C T

The evolution of Forest Sector Models (FSMs) since the 1960s has marked a significant advancement in forest economics and policy analysis. However, this development is limited to North America and Europe's nations; tropical countries, crucial for biodiversity, carbon storage, and deforestation, face a notable scarcity of FSMs, often attributed to the limited and fragmented nature of their forest sector data. The importance of unprocessed wood and sources of wood supply are also distinct in tropical countries. We address these issues by introducing a comprehensive framework to build FSMs tailored for tropical countries whose national accounts are aligned with United Nations standards. We demonstrate the applicability of our framework by constructing the Colombian Forest Sector Model (CFSM), a structural econometric partial equilibrium model. The CFSM includes five markets grouped in two market sub-models: one for unprocessed wood (firewood and industrial wood) linked to a forest plantations simulator, and other for manufactured wood products (wood, furniture, and pulp & paper). The model consists of 32 behavioral equations, explaining supply, consumption, exports and imports, and prices for consumption and trade for each market, plus 18 summation and market-clearing identities. Model estimation is based on 41 years (1975–2015) of data collected, organized, and transformed through a meticulous process. Rigorous validation confirms the CFSM's robustness and reliability. The model's application is demonstrated by estimating wood availability and impacts under several plantation expansion scenarios, and the monetary effects of expanding Colombia's wood products industry. The paper opens new frontiers of research in FSMs.

1. Introduction

Forest Sector Models (FSMs), a critical branch in the fields of forest economics and policy analysis, has one major gap—the lack of forest sector models for tropical countries; this paper makes the first fundamental contribution to this gap that persisted for more than 55 years. Rivière and Caurla (2021), who define FSMs as “large-scale partial equilibrium models of the forest sector that represent natural, technological, and economic facts together with their interactions that enable the determination of product prices and supply and demand quantities”, trace their origins to the mid-1960s with the pioneering work of W.L.M. McKillop. McKillop (1967) built a partial equilibrium model of the United States forest sector, whose specification consisted of linear supply and demand equations that aimed to unravel the intricate dynamics of price formation and consumption levels across various timber products.

Building on McKillop's initial efforts, several other FSMs emerged in the United States (U.S.) before the mid-1970s, each focusing on specific aspects of the forest sector. Notable among these were Adams (1974) timber market model in Douglas fir regions, Robinson (1974) econometric model of softwood lumber and stumpage markets, and Haynes

(1975) dynamic spatial equilibrium model for softwood timber, all of which played pivotal roles in shaping the theoretical approaches and methodologies fundamental to FSM development (Buongiorno, 1996). The 1980s then saw a significant shift towards the integration of these efforts, culminating in the development of comprehensive FSMs like the Timber Assessment Market Model (TAMM) by Adams and Haynes (1980), which became a widely used tool for policy analysis in U.S. forest markets, allowing for long-term projections of prices, consumption, and production in stumpage markets (Adams and Haynes, 1980; 1993). Recognizing the focus of TAMM on the solid wood sector, the PAPHYRUS model was developed to complement it, focusing on the U.S. pulp and paper industry, later evolving into the North American pulp and paper model (NAPAP) (Gilles and Buongiorno, 1987). Concurrently, the scope of FSM development extended beyond the U.S. with the introduction of the IIASA Forest Sector Model or Global Trade Model (GTM) by Kallio et al. (1987), representing 16 forest products traded across 18 global regions, considering bilateral trade linkages, transportation costs, tariffs, and trade barriers. The GTM later evolved into the CINTRAFOR GTM, expanding its scope to more products and regions (Buongiorno et al., 2003a; Turner and Buongiorno, 2003). By the late 1990s, global models like the Global Forest Products Model (GFPM)

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(Zhang et al., 1997; Buongiorno et al., 2003b) and the Timber Supply Model (TSM) by Sedjo and Lyon (1996) had emerged, projecting future prices and quantities for forest products across multiple regions. During the 1990s and the 2000–2013 period, additional recursive dynamic models such as the Finnish SF-GTM (Ronnila, 1995), the Norwegian NTM (Trømborg and Solberg, 1995), the US South sub-regional timber supply model STSM (Abt et al., 2000), the European Forest Institute Global Trade Model EFI-GTM (Kallio et al., 2004), NTM II (Folstrand Bolkesjø et al., 2006), the French forest sector model FFSM (Caurla et al., 2009; Caurla et al., 2010), and the United States Forest Product Module USFPM of the GTM (Ince et al., 2011) contributed to the landscape, alongside inter-temporal optimization models like the Forest and Agriculture Optimization Model FASOM (Adams and Haynes, 1996), the US Pacific Northwestern Regional Models PNW-RM (Schillinger et al., 2003), the Norwegian Nor-For (Sjølie et al., 2011), and the European FASOM (Schneider et al., 2008; Lauri et al., 2012). The forward-looking dynamic Model of Global Timber Markets (Sohngen et al., 1999; Sohngen and Mendelsohn, 2003) also emerged during this time. Between 2013 and 2020, new FSMs were introduced, including the Alberta FSM (Niquidet and Friesen, 2014), the global REPA-PFC Forest Trade Model RPFTM (Van Kooten and Johnston, 2014), the Nordic FSM (Mustapha, 2016), and the updated French FFSM++ (2016), further expanding the field. The evolution of FSMs since the 1960s is comprehensively documented in the works of Solberg (1986), Haynes (1993), Buongiorno (1996), Adams and Haynes (2007a, 2007b), Latta et al. (2013), Sjølie et al. (2015), Rivière and Caurla (2021), and Martínez-Cortés (2023), with the foundational models like TAMM, PAPYRUS, and GTM credited with shaping the current generation of FSMs (Latta et al., 2013; Rivière and Caurla, 2021).

Shortly after their introduction, FSMs quickly became essential for analysis and policy deliberation in the forest sector (Latta et al., 2013; Sjølie et al., 2015). The evolution in FSM usage, as Rivière and Caurla (2021) observe, extends beyond their original scope of timber markets and forest resource management, now increasingly addressing broader concerns such as climate change mitigation and energy production. In policy analysis, the central role of FSMs echoes the principles set forth by Hawkesworth (1988), strategically dissecting complex policy issues, elucidating policy debate intricacies, pinpointing argumentative weaknesses, and clarifying the ramifications of various policy options. A pivotal paper by Sedjo and Goetzl (1997), titled “Workshop to Examine Models Needed to Assist in the Development of a National Fiber Supply Strategy for the 21st Century”, offers compelling instances that underscore the versatility of FSMs, extending beyond the initial commodity-focused policies to encompass environmental considerations. Adams and Haynes (2007b) provide an extensive overview of the diverse applications of FSMs in forest policy analysis up to the mid-2000s, categorizing them into themes such as balancing commodity and non-market resource values, detailed resource planning, and exploring the interplay of forest policy with other sectors. Recent advancements in FSMs, tackling a diverse array of policy issues such as forest conservation, bioenergy, environmental challenges, renewable energy, and climate change at various geographical levels, have been comprehensively reviewed by Toppinen and Kuuluvainen (2010), Latta et al. (2013), Guo et al. (2019), Rivière and Caurla (2021), and Martínez-Cortés (2023). Noteworthy examples include the integration of FSMs into the Timber Assessment Projection System (TAPS) in the United States since 1980 (Adams and Haynes, 2007a). Additionally, the application of FSMs in analyzing trade impacts and climate change has also been significant, with studies by Bishop (1997) on tropical timber, Perez-Garcia et al. (1997) on climate change, and Kallio et al. (2006) on forest conservation in Europe. Buongiorno et al. (2011) examined the impact of bioenergy demand on the global forest sector, while Guo et al. (2019) provided insights into the regional implications of increased bioenergy production, and Favero et al. (2018) and Favero et al. (2021) further explored climate change impacts on forest ecosystems and markets. These examples underscore FSMs’ adaptability and their

critical role in shaping contemporary forest policy and management strategies.

Both the evolution of FSMs and their usage in forest policy analysis have been reported at national, regional, and global scales (Toppinen and Kuuluvainen, 2010). At country-scale, however, the development and use of FSMs have predominantly centered on temperate nations, particularly North America and Europe. Tropical countries, which are global centers of biodiversity richness, carbon storage, and deforestation, experience a notable scarcity in both the building and application of national-scale FSMs (Martínez-Cortés, 2023).¹ This issue of a significant divide in forest sector modeling between developed and tropical nations was first highlighted by Haynes (1993) after the 10th Forestry World Congress. Haynes (1993) observed that in tropical countries forest data is restricted to international trade records or limited to select wholesalers; and the data from local sources and from the World Bank and FAO are insufficient in providing specific statistics crucial for FSMs, such as local market data on forest product prices and quantities.

To address the data challenges highlighted by Haynes, the use of National Accounts as data source for developing national-level FSMs presents a promising solution but remains underexplored. A notable and only example reported in scientific literature of this approach is the Canadian Forest Product Sector Model (CFPSM) (Kant et al., 1996), which effectively integrates National Accounts into its conceptual framework. The CFPSM leverages comprehensive data on forest sector production, consumption, international trade, and pricing at the national level. It is also integrated within the broader FOCUS Canada macroeconomic model (Dungan et al., 1995), demonstrating a synergistic interaction between sector-specific and national economic data. While the CFPSM primarily examines the influence of national economic variables on the forest sector, it also highlights the sector’s potential impact on the broader economy. Although developed in a temperate country, the innovative methodology used in the CFPSM offers valuable insights that could be adapted to overcome data scarcity and development challenges in FSMs for tropical countries.

In this paper, we build upon the approach of Kant et al. (1996) to address the challenges of developing national-scale FSMs for tropical countries. We propose a comprehensive framework, developed as part of the first author’s doctoral thesis, that encompasses theoretical, conceptual, methodological, and empirical aspects of building national-scale FSMs tailored for tropical countries. This framework is particularly suited for countries with national accounting systems aligned with the United Nations standards and is designed to accommodate all forest products—including wood and non-wood forest products, as well as forest ecosystem services—with existing or foreseeable markets. Using Colombia as a case study, we demonstrate the effectiveness and adaptability of our framework through the development of the first phase of the Colombian Forest Sector Model (CFSM), which focuses on wood forest products. The CFSM has been employed to analyze the country’s current forest policy, a topic that is explored in several other papers.

In proposing our framework and developing the CFSM, we also illustrate how to address five key considerations specific to national-scale FSMs for tropical countries—areas that have received limited attention in previous FSM research. First, building FSMs requires a considerable amount of both forest sector and socioeconomic data, which is often consolidated, centralized, and accessible in temperate

¹ Tropical countries have been included in global FSMs, such as the GTM and the GFPM. Additionally, the forest sectors of several tropical countries have been analyzed using Multisectoral Input-Output and General Equilibrium (GE) models, including Computable General Equilibrium (CGE) models, as well as descriptive and GAP models (commissioned by FAO, and UNECE), and forest carbon models (e.g., FORCARB, and HARVCARB). However, the capabilities of these models and the analyses they enable differ from those of FSMs. For distinctions of these models from FSMs, refer to Haynes (1993), Banerjee & Alavalapati (2014), and Martínez-Cortés (2023).

regions but tends to be fragmented in tropical regions. While much of this key data resides within the national accounts system, it may not always be fully accessible or consolidated. Additionally, forest sector data not included in national accounts is often collected by various government and non-government agencies, and socioeconomic data faces similar challenges due to multiple sources and inconsistent reporting. This fragmentation complicates the collection, compilation, and consolidation of data required for FSM development. We overcome this by developing a comprehensive data consolidation process that meticulously collects, organizes, and transforms both historical and current data.

Second, while FSMs have generally focused on manufactured wood product markets, unprocessed (raw) wood markets have received less attention, particularly due to their relatively minor role in developed economies. However, in tropical countries, markets of unprocessed wood—used for firewood and for the manufactured wood products industry and final consumption other than firewood—play a crucial role and significantly contribute to the economy. For example, the importance of the firewood market is substantial; in 2022, 74 % of the 1.97 billion cubic meters of global production wood fuel was produced in tropical countries (FAO, 2024). In Colombia, the production of firewood alone amounted to 4.7 million tons, while industrial wood production totaled 4.58 million cubic meters of underbark roundwood in 2021 (Martínez-Cortés, 2023; MADR, 2023; MADS, 2023; DANE, 2023; FAO, 2023). We manage this by including two distinct markets of raw wood: one for unprocessed wood for firewood and another for raw wood used in the manufactured wood products industry and final consumption other than firewood, in addition to the traditional focus on manufactured wood products.

Third, in tropical countries, wood supply is not limited to natural forests and commercial plantations, as it often is in temperate/developed economies, and agroforestry and trees outside forests are two important sources of wood supply. In Colombia, for instance, the area of agroforestry systems (including those with coffee, cocoa, and livestock) is considerable and can surpass the country's area of commercial forest plantations, which was 0.54 million hectares in 2022 (MADR, 2023). Additionally, trees outside forests (planted and naturally regenerated) have become increasingly relevant in Colombia and are growing (ICA, 2021). Although the exact volume of unprocessed wood supplied from these sources is currently unclear, this trend is expected to grow in the future. We incorporate all four sources of wood supply—natural forests, commercial plantations, agroforestry systems, and trees outside forests—to provide a comprehensive analysis.

Fourth, many existing FSMs for temperate countries are purely economic models that lack integration with biophysical models of forests. These linkages are essential, particularly for policy analysis related to wood supply from different sources, such as commercial plantations. We handle this by linking forest ecosystem simulators (forest growth and yield models) to market models. This integration allows us to incorporate physical wood supply as a key explanatory variable in the wood supply equations. Specifically in the phase I of the CFSM we thoroughly developed the simulator for forest plantations and linked it to the market model of the unprocessed wood for industrial uses.

Fifth, transparency is a critical challenge for FSMs, impacting their accuracy and reliability. As highlighted by Toppinen and Kuuluvainen (2010), the complexity of FSMs often results in a lack of transparency, making it difficult to assess their underlying assumptions and mechanisms. This opacity can undermine confidence in the model's predictions and hinder effective policy analysis. To address these issues, we developed a comprehensive and detailed documentation on the CFSM's assumptions, mechanisms, and validation process. We also created an Excel® App to perform an extensive model's validation which retains all the original time series used for model estimation. The App also executes (solves) the CFSM and keeps all the inputs and the output of the execution. This App, together with our thorough explanation of the model's assumptions and mechanisms, and our extensive data

consolidation process, effectively addresses potential transparency challenges. This approach not only ensures the CFSM's accuracy and reliability but also sets a standard for modeling practices in tropical regions.

Next, we present our comprehensive framework for building FSMs for tropical countries, which is detailed in Sections 2 to 5. Section 2 introduces the general structure and specification approach for any FSM, designed to accommodate all forest products—including wood and non-wood forest products, as well as forest ecosystem services—along with all sources of these products, such as forest plantations, natural forests, and trees outside forests. In Section 3, we provide a detailed specification of an FSM focused exclusively on wood forest products, exemplified by the Colombian Forest Sector Model (CFSM). Section 4 discusses the methods and data used for the CFSM estimation, while Section 5 presents the results of the estimation and validation of the model. Model applications are outlined in Section 6. Section 7 ends the paper with the main conclusions, limitations, and future research directions.

2. Structure and specification of a general forest sector model – FSM

2.1. The forest sector modeled

Generally, the forest sector is considered as an integration of forest-related activities, and different authors have emphasized different activities in their forest sector modeling. For example, Solberg (1986, p.420) considered forestry and forest industries and interactions between them, while Buongiorno (2014, p. 291) focused on activities related to the growing, harvesting, transportation, and transformation of wood into wood products, and the use of wood products. Rivière and Cauria (2021) reviewed several approaches for modeling the forest sector and concluded that in modeling the forest sector it should be considered that the forest sector is “extensive and intricate, characterized by the inclusion of horizontally and vertically integrated structures and processes (Johnston & van Kooten 2014) but also of different natures: biological dynamics, economic behaviours, and industrial processes” and more.

For the development of our FSM, we adopted the comprehensive approach of Gane (2007, p. 32), illustrated in Fig. 1. His forest sector concept encompasses three components: resources, activities, and outputs, all of which are intertwined in both space and time. It is important to note that Fig. 1 implies that anything not intrinsically related to forests falls outside the forest sector. In the forest sector, the resource component is made up of natural, human, and capital assets. Natural resources correspond to the forest ecosystems, with natural forests, commercial and other types of forest plantations, agroforestry systems, trees outside forest, and other forest lands representing variations of these ecosystems. The component of activities comprises the primary production, arising from silviculture, i.e., the management of forest ecosystems to obtain one or more forest products (initially with minimal or no processing), transformation (aka manufacturing), trade (aka commercialization), distribution, and consumption. The output component of the forest sector is jointly known as forest products, which are either goods (i.e., tangible things) or services (non-tangible things). Goods are classified into two main groups: wood forest products (WFP) and non-wood forest products (NWFP). Services are usually referred to as forest ecosystem services (FES).

The WFP include unprocessed wood (e.g., logs and roughly squared wood -blocks- sometimes obtained from forests by using chainsaws or other means), and manufactured wood products (e.g., sawn wood, wood furniture, wood-based panels, pulp, paper, and paperboard). Unprocessed wood comprises not only firewood and logs & blocks for industrial use and for final consumption other than firewood, but also “forest biomass” which, in some cases, is used to feed power plants. The NWFP includes tree exudates such as rubber and rosin, barks, and leaves, among others. The FES comprises carbon capture and storage,

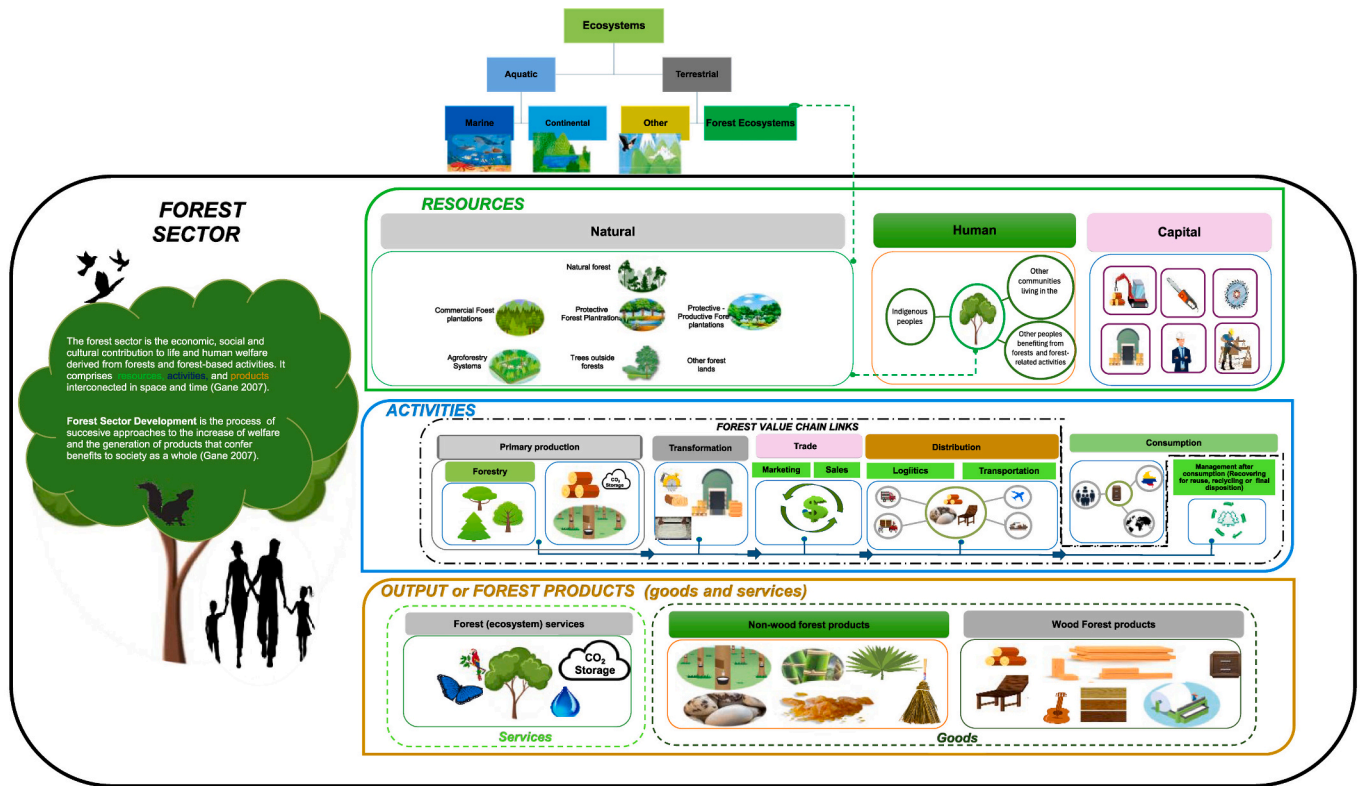


Fig. 1. The Forest Sector Concept. Source: Martínez-Cortés (2023)

biodiversity conservation, water protection, and nature tourism, to name a few.

All WFP, and many NWFP and FES could be traded in a market. Currently, these markets are at different stages of development. In general, there exist markets for most of the WFP and many NWFP which can be either formal or informal. In contrast, there are only a few markets for FES (e.g., those related to carbon capture and storage, biodiversity conservation, and water protection and regulation) and these are usually formal. Given the characteristic that many forest products can be traded in a market, our way of thinking about the forest sector for modeling purposes in the context of this paper is as the aggregate of all existing markets of WFP, NWFP, and FES.

2.2. General structure of a forest sector model (modeling approach, markets, products, components, and phases)

To represent a country’s forest sector, we use a structural economic partial equilibrium model based on the framework of neoclassical competitive market theory. This market model is connected to a series of simulators that emulate the biological behavior of forest ecosystems, including natural forests, forest plantations, agroforestry systems, and trees outside the forest.

The FSM captures the total existing market for all forest products, which are divided into three aggregated markets: the WFP market, the NWFP market, and the FES market. Aggregation in these markets refers to the sum of the individual markets of every product (good or service) within each category of forest products. Each individual market of a product within the WFP and NWFP categories consists of the addition of two markets related to the level of processing of the product: unprocessed or manufactured (processed). We consider unprocessed WFP and NWFP as those forest products at the state they are in when harvested (i.e., without any or with minimal transformation process) from forest ecosystems. In addition, we think of manufactured WFP and NWFP as those produced by the manufacturing industry. This common division of

forest products based on their degree of processing allows us to also group the markets captured in the FSM as two aggregated markets: one for the unprocessed forest products and one for the manufactured forest products. Since FES do not go through any manufacturing process before human’s consumption, we place their aggregate market under the unprocessed forest products market.

A complete conceptual map for the development of the FSM is presented in Fig. 2. The model features two types of components: market sub-models (in yellow boxes at the center of the figure), and forest ecosystems simulators (in blue boxes on the left). The Unprocessed forest products market sub-model (UFM) and Manufactured forest products market sub-model (MFM) comprise the partial equilibrium models (PEMs) that mimic the behavior of the markets mentioned in the preceding paragraph. In addition to the PEMs, in the yellow box of the UFM we have included one of the most important variable inputs into the PEMs, named Available Stock for Supplying (AS), which is derived from the area change and biological behavior of the forest ecosystems for each category of forest products: WFP, NWFP, and FES. The AS variable is a key policy variable into the model which allows the modeler to run policy experiments, and in the FSM it is the combined output of the simulators for natural forest, forest plantations, agroforestry systems, and trees outside forest.

As the range of forest products is vast, the FSM can be developed in phases, each adding incremental complexity to the model while introducing new features and capabilities for more advanced forest sector studies and policy analysis. At its simplest, the model may consist of a single partial PEM representing just one individual market at a specific degree of processing, such as the market for manufactured rubber, CO₂ offsets, or unprocessed wood for firewood. Alternatively, it can incorporate two PEMs to represent aggregated markets by degree of processing, such as the unprocessed wood market and the manufactured wood products market, without delving into specific product subdivisions—for instance, distinguishing between firewood and industrial wood within the unprocessed wood market, or manufactured wood

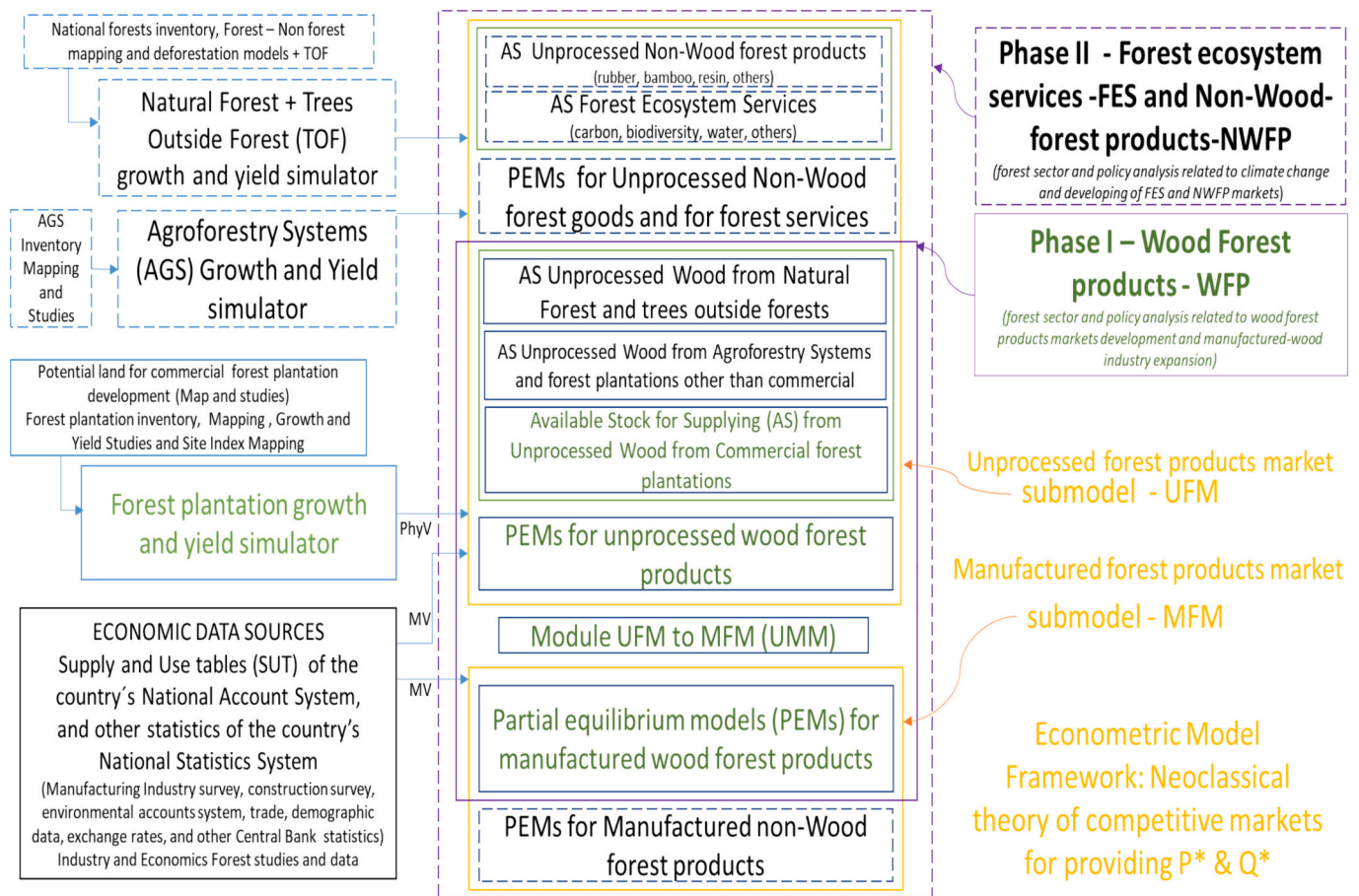


Fig. 2. Conceptual map for a forest sector model (FSM). Source: Modified from Martínez-Cortés (2023). PhyV: Physical Values, MV: Monetary Values, P*: Equilibrium prices, Q*: Equilibrium quantities. The Module UFM to MFM (UMM) facilitates communication between the two submodels by converting monetary values into physical values using physical conversion factors (quantities of unprocessed product needed to obtain a manufactured product) and monetary conversion factors (monetary volume quantities/price of a product to obtain physical quantities). For further explanation of these conversion factors, see Martínez-Cortés (2023).

products from the wood, furniture, and pulp and paper industries within the latter. For more detailed analysis, multiple PEMs can be employed to represent various individual markets within the forest sector, as further explained. In Fig. 2, we highlight two phases (in magenta boxes), though other configurations with more aggregated or disaggregated phases are also possible. In the example shown, Phase I focuses solely on wood forest products (WFP), enabling the model to conduct experiments related to the development of WFP markets and the expansion of the manufactured wood industry, mainly. Phase II, which includes non-wood forest products (NWFP) and forest ecosystem services (FES), enhances the model's capacity to perform more complex experiments related to the development of NWFP and FES markets and the broader role of forests in addressing climate crises, beyond what is possible with just Phase I.

The lower left corner of Fig. 2, bordered by a black box, identifies the sources of economic data essential for estimating the model. These include the Supply and Use tables from a country's National Accounts System, as well as other data typically collected under what can be broadly categorized as the country's National Statistics System. More detailed information on these sources and the data used for model estimation is provided in subsequent sections of this paper.

2.3. General specification a forest sector model

Based on the mapping illustrated in Fig. 2 and explained in the preceding section, the general form of the theoretical structure of the

proposed FSM, summarized in terms of identities and behavioral equations, is as follows.

2.3.1. Identities

Each partial equilibrium model for any and all aggregated markets and its individual markets captured by the FSM is centered around the Market Clearing Condition (MCC) concept, which assumes that markets are in equilibrium. In other words, we assume that, at any point in time, total supply (ST) equals total demand (DT).

$$ST_t = DT_t \text{ (Identity 1)}$$

Identity 1 is used to determine the prevailing price if MCC holds; if not, price is factored in as an exogenous variable. In general form, the Supply side (ST) of the identity 1 captures the sum of the supplies (S) of all three aggregated forest sector markets defined at the start of Section 2.2 — i.e., the markets of WFP, NWFP, and FES.

$$ST_t = \sum S_t \text{ (Identity 2)}$$

By extension, the supply of each aggregated market (S) is in itself the sum of the supplies from all its individual markets. As an example, the total supply for the WFP market is the addition of the supplies of the unprocessed wood market and the manufactured wood products market, and this latter is in turn the sum of the supplies of its industries (i.e., wood, furniture, pulp & paper).

As defined by economic theory, the Demand side (DT) of the identity 1, which represents the total Demand for all products of the forest sector,

is defined as the sum of total public and private domestic consumption (CT) plus total exports (XT), minus total imports (MT).

$$DT_t = CT_t + XT_t - MT_t \text{ (Identity 3)}$$

Modeled this way, it facilitates the analysis of the effects of different policies on specific components of a country's economy, such as GDP and trade balances. At the aggregate market level, each Demand component is the sum of all the individual markets it represents.

$$CT_t = \sum C_t \text{ (Identity 4)}$$

$$XT_t = \sum X_t \text{ (Identity 5)}$$

$$MT_t = \sum M_t \text{ (Identity 6)}$$

2.3.2. Supply, consumption, exports, and imports behavioral equations

At the individual market level, according to economic theory, the supply (right-hand side of Identity 2) of a good (or service) depends upon its price and production costs, which are, in turn, affected by the price and availability of the input factors, such as labor, capital, materials, and energy. Both the prices of the good (or service) and of the input factors, as well as the availability of the latter are considered by economic theory as the key determinants of supply. Supply is also affected by changes in natural conditions (e.g., weather), shifts in production technology, and government policies (e.g., taxes and subsidies).

Similarly, the behavior of consumption, exports, and imports in individual markets (right-hand side of Identities 4, 5, and 6) is shaped by a combination of domestic and global variables. According to economic theory, consumption of a good (or service) is influenced by key factors such as its price, consumer income, and wealth. It is also affected by the prices and availability of related goods (whether substitutes or complements), changes in consumer preferences and tastes, government policies, expectations about future prices and income, and interest rates. Exports of a good (or service) depend on its price, exchange rates, and global demand, and are also influenced by trade policies and the competitiveness and productivity of the domestic industry. Imports are similarly influenced by exchange rates, global prices of the good (or service), and domestic consumption levels of it. Additionally, imports are affected by domestic income levels, trade policies, and the production costs and competitiveness of the importing country's industry that produces the good (or service) under consideration.

The relationship between supply, consumption, exports, and imports, and the corresponding variables on which they depend, forms the basis of the behavioral equations in our general FSM. For brevity, we do not present these equations for each individual market within the aggregated WFP, NWFP, and FES markets that can be included in a FSM. Instead, in the next section, we illustrate the theoretical formulation of these equations for one specific market—the WFP market—within the context of a case study for Colombia. This case study uses a national-scale FSM, named the Colombian Forest Sector Model (CFSM), which corresponds to Phase I shown in Fig. 2, and was designed using the framework presented thus far and estimated as part of the first author's doctoral thesis.

3. Structure and specification of a country-specific forest sector model: a case study of Colombia

3.1. Structure of the Colombian forest sector model (CFSM)

The general outline of the CFSM is presented in Fig. 3, which provides a zoomed-in view of the components of our general FSM (Fig. 2) that were fully developed for the model discussed in this section. There are three main components for the CFSM: two market models—the manufactured wood products market sub-model (MWM) and the unprocessed wood market sub-model (UWM)—, and the Colombian Forest

Plantation Growth and Yield Simulator (SCRPF). The structures of the MWM and UWM are explained in the following subsections. The SCRPF, which utilizes a biological model to project the volume availability of unprocessed wood from Colombia's forest plantations, is used in the CFSM to provide the volumes available for the supply of unprocessed wood (a variable in the behavioral equations of the UWM named VAST). This volume is an input for the manufactured wood product industry. Note that, for the current version of the CFSM, it is assumed that wood from forest plantations is not used for final consumption, such as firewood or other uses. The simulator, together with an empirical exercise outlining the availability of unprocessed wood from forest plantations for the period 2015–2047 under various commercial plantation expansion scenarios for Colombia, is detailed in Martínez-Cortés et al. (2022).

Fig. 3 does not include the simulators for agroforestry systems, natural forests, and trees outside forests that are depicted in Fig. 2, as these components were not developed for the current version of the CFSM due to data restrictions. However, since these three sources of wood are crucial for Colombia's WFP market, we employ an alternative approach to integrate them into the current version of the CFSM, which will be explained later. Additionally, the forest bioenergy industries and other innovative manufactured wood products industries, indicated by the dashed box within the MWM in Fig. 3, were also not included in the current version of the CFSM due to similar data limitations. These industries are included in the Fig. 3 to highlight their importance and to remind readers that any other country considering a FSM with a MWM should not neglect the individual markets for products of these industries.

In the CFSM, the UWM and MWM together represent the aggregated market for wood forest products (WFP). The UWM reflects the behavior of the unprocessed wood (UW) or raw wood (rw) market, which is in itself an aggregate of two individual smaller-scale markets: Unprocessed wood for manufactured wood products industry and final consumption other than firewood (MWrw), and Unprocessed wood for firewood (FWrw). On the other hand, the MWM accounts for the behavior of the manufactured wood products (MW) market, which is the aggregate of the three individual smaller-scale markets for the manufactured products of the: wood industry (w), furniture industry (f), and pulp and paper industry (z). Additional details of the markets and products considered under the CFSM are presented in Appendix A.

In the MWM and UWM each of the two markets making up the WFP market—the rw market and the MW market—is represented by several partial equilibrium models (PEMs), as shown in Fig. 3. The MWM includes three PEMs, for w, f, and z individual markets respectively. The UWM comprises two PEMs, one for FWrw market and one for MWrw market. Every PEM is a system of simultaneous linear equations which includes several behavioral equations and one identity for the market clearing condition (MCC). In each PEM, behavioral equations explain the total supply (national production), consumption, trade (exports & imports), and prices for consumption and trade. The specifications for the identities and theoretical behavioral equations of the CFSM are summarized in Table 1, with detailed explanations provided in the following subsections. For the sake of parsimony, both the identities and equations in this section are presented in their general form and apply to both sub-models of the CFSM (MWM and UWM), unless otherwise specified. Readers interested in the specific theoretical behavioral equations for each market considered in the CFSM can consult Martínez-Cortés (2023). This reference also includes the corresponding market identities that complete each PEM within both sub-models (UWM and MWM) and the overall CFSM.

3.2. Specification for the CFSM: identities and behavioral equations of the sub-models MWM and UWM

3.2.1. Market-specific identities

Following the general form presented in Section 2, the CFSM

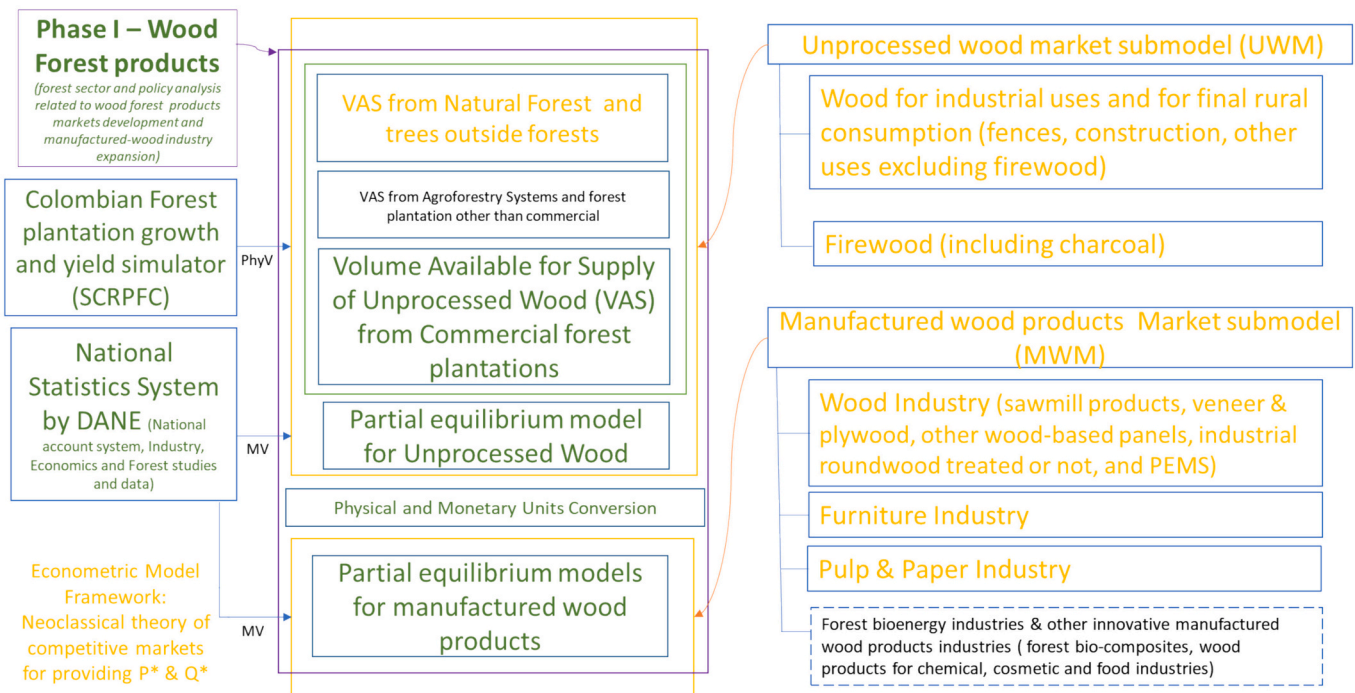


Fig. 3. Conceptual map of the Colombian forest sector model (CFSM).

Source: Modified from Martínez-Cortés (2023). PhyV: Physical Values, MV: Monetary Values, P*: Equilibrium prices, Q*: Equilibrium quantities, PEMS: secondary processed wood products (productos madereros de elaboración secundaria, in Spanish). In green: data, inputs, and sources available up to 2021 and parts of the UWM and MWM fully developed under the CFSM. In yellow: data that need improvement (e.g., the UWM sub-model currently includes a detailed specification only for calculating the wood supplied by commercial forest plantations. Unprocessed wood from natural forests is incorporated as a lump sum, i.e., without a simulator for natural forests. When data from the national forest inventory become available, a simulator for the dynamics of natural forests can be developed and incorporated). The forest bioenergy industry and other innovative manufactured wood products (right bottom corner) are to be developed in the future as these industries evolve.

incorporates a general market clearing identity (Identity 1 in Table 1) applicable to all aggregated and individual markets considered: WFP, MW, and rw (aka UW). For these markets, total supply (ST) is a composite of the supply (S) of each smaller-scale market within them (Identity 2 in Table 1). Specifically, ST for the WFP market is the sum of the supplies from the MW and rw markets. Within the MW market, supply is the sum of the supplies from the w, f, and z industries. In the case of the rw market, supply is the sum of supply from Colombia’s commercial forest plantations (fp), natural forest (nf), agroforestry systems (as), and trees outside forests (to). Therefore, ST for the rw market is the aggregate of the supplies of unprocessed wood from these four sources.

However, due to an increasing interest in forest plantation development by Colombia’s government (Martínez-Cortés et al., 2022) and the data constraints mentioned earlier in this section, the current version of the CFSM provides a detailed specification only for wood supply from commercial forest plantations, through the calculations of VAST from this source with the help of the SCRPFPC. Wood supply from natural forests is included in the CFSM through a basic equation that does not rely on VAST from this source, as we will discuss later. The current version of the CFSM also has an alternative way to include the wood supply from natural forest which is a lump-sum estimation based on trends in the historical supply, as per the national wood consumption balances. Additionally, wood supply from agroforestry systems is currently accounted for within the volumes supplied from commercial forest plantations, while wood supply from trees outside forest is included within the volumes of both commercial forest plantations and from natural forests. However, no separate specification exists for agroforestry systems and trees outside forests in the current version of the CFSM. The complete specification for the supply from the sources outside of commercial forest plantations will be addressed in future versions of the CFSM. A more detailed breakdown of the supply

determinants for the rw market considered under the sub-model named UWM, with a special focus on how the VAST variable is calculated, is provided in Appendix B.

A similar explanation applies to the Total Demand (DT) for the markets of WFP, rw, and MW, as outlined for ST. This total demand is detailed in Identity 3 of Table 1, and is similarly broken down into its components: Total Consumption (CT), Total Exports (XT), and Total Imports (MT), as expressed in Identities 4, 5, and 6 of the same table. At the most basic level of the smaller-scale markets—identified as sub-market *k* in Table 1, which includes the markets for MW_{rw}, FW_{rw}, w, f, and z—the market clearing condition also applies (Identity 7). The behavioral equations for Supply (S) and the components of Demand (D) at these basic levels within the MWM and UWM sub-models of the CFSM are detailed below.

3.2.2. Supply-specific behavioral equations

The supply (S) equations of the three individual markets under MWM (Eq. 8 in Table 1) include four explanatory variables: labor (L) and capital (K) specific to the domestic industries producing w, f, and z, respectively; the prices of supply (PS) for the w, f, and z products produced by these industries, correspondingly; and the price of consumption, PC, of the unprocessed wood for the manufactured wood products industry and final consumption other than firewood, MW_{rw} (PC_i^{MW_{rw}}).

In these three supply equations, we have not included any explanatory variables for changes in natural conditions and technology, government policies, energy, and most of the materials but MW_{rw}, for three reasons: 1) they have had null or negligible effects on the Colombian wood forest products industry in the past seven decades, and/or 2) it was already known (at the time of formulating the theoretical equations) that their data was scarce, and/or 3) to comply with Occam’s razor principle. Note that we equate supply with national production.

In the supply equations of the two individual markets within UWM,

Table 1
Theoretical Behavioral Equations and Identities for the CFSM.

Identity or Equation Number	Identity or Equation name	Identity or Equation
1	Clearing Condition for market j, where j = {MW, rw (aka UW), WFP}	$ST_t^j = DT_t^j$
2	Total Supply (Production) in market j over all markets k (of j), where k = {w, f, and z for MW and MWrw and FWrw for rw whit MWrw = MWfprw + MWNfrw and FWrw = FWNfrw}	$ST_t^j = \sum_k S_t^{kj}$
3	Total Demand for market j	$DT_t^j = CT_t^j + XT_t^j - MT_t^j$
4	Total Consumption in market j over all markets k	$CT_t^j = \sum_k C_t^{jk}$
5	Total Exports in market j over all markets k	$XT_t^j = \sum_k X_t^{jk}$
6	Total Imports in market j over all markets k	$MT_t^j = \sum_k M_t^{jk}$
7	Clearing condition for each market k	$S_t^k = C_t^k + X_t^k - M_t^k$ (i.e. $S_t^k = D_t^k$)
8	Supply for each market k where $\beta_5^{sk} = 0$ for k = {MWfprw, MWNfrw, FWNfrw}, $\beta_8^{sk} = 0$ for k = {MWNfrw, FWNfrw}, and $\beta_6^{sk} = \beta_7^{sk} = 0$ for k = {w,f,z}	$S_t^k = \beta_1^{sk} + \beta_2^{sk} PS_t^k + \beta_3^{sk} L_t^k + \beta_4^{sk} K_t^k + \beta_5^{sk} PC_t^{MWrw} + \beta_6^{sk} VAST_t^k + \beta_7^{sk} GEN_t^k + \epsilon_t^{sk}$
9	Consumption in each market k of the manufactured wood products market where $\beta_6^{ck} = 0$ for k = z and $\beta_8^{ck} = 0$ for k = {w,f}	$C_t^k = \beta_1^{ck} + \beta_2^{ck} PC_t^k + \beta_3^{ck} U_t + \beta_4^{ck} i_t + \beta_5^{ck} W_t + \beta_6^{ck} HCS_t + \beta_7^{ck} Y_t + \beta_8^{ck} N_t + \epsilon_t^{ck}$
10	Consumption in each market k of the unprocessed wood market where $\beta_2^{ck} = \beta_4^{ck} = \beta_5^{ck} = \beta_6^{ck} = \beta_7^{ck} = \beta_8^{ck} = 0$ for k = FWrw and $\beta_5^{ck} = \beta_6^{ck} = \beta_{10}^{ck} = \beta_{11}^{ck} = 0$ for k = MWrw	$C_t^k = \beta_1^{ck} + \beta_2^{ck} U_t + \beta_3^{ck} PC_t^k + \beta_4^{ck} NR_t + \beta_5^{ck} W_t + \beta_6^{ck} Y_t + \beta_7^{ck} i_t + \beta_8^{ck} GEO_t + \beta_9^{ck} S_t^{sw} + \beta_{10}^{ck} S_t^c + \beta_{11}^{ck} S_t^{cz} + \epsilon_t^{ck}$
11	Exports in each market k	$X_t^k = \beta_1^{sk} + \beta_2^{sk} IP_t + \beta_3^{sk} PX_t^k/RX_t + \epsilon_t^{sk}$
12	Imports in each market k, where $\beta_4^{mk} = \beta_5^{mk} = 0$ for k = FWrw	$M_t^k = \beta_1^{mk} + \beta_2^{mk} C_t^k + \beta_3^{mk} PC_t^k/PM_t^k + \beta_4^{mk} CUR_t^k + \beta_5^{mk} VAST_t^k + \epsilon_t^{mk}$
13	Consumption price in each market k	$PC_t^k = \beta_1^{ck} + \beta_2^{ck} S_t^c + \beta_3^{ck} PC_{t-1}^k + \epsilon_t^{ck}$
14	Export price in each market k	$PX_t^k = \beta_1^{sk} + \beta_2^{sk} PX_{t-1}^k + \beta_3^{sk} RX_t + \beta_4^{sk} WEPI_t^k + \epsilon_t^{sk}$
15	Import price in each market k	$PM_t^k = \beta_1^{mk} + \beta_2^{mk} PM_{t-1}^k + \beta_3^{mk} PC_t^k/PC_{t-1}^k + \beta_4^{mk} RX_t + \epsilon_t^{mk}$
	$PC_t^z = \beta_1^{cz} + \beta_2^{cz} S_t^z + \beta_3^{cz} PC_{t-1}^z + \epsilon_t^{cz}$ (Eq. 13 for k = z)	
	PC_t^z : Consumption price of the manufactured wood products of the pulp and paper industry at time t	
	$\beta_1^{cz}, \beta_2^{cz}, \beta_3^{cz}$: First (Independent), second and third population parameter of the equation of price of consumption for the manufactured wood products of the pulp and paper industry, respectively.	
	S_t^z : Supply (production) of manufactured wood products of the pulp and paper industry at time t	
	PC_{t-1}^z : Consumption price of the manufactured wood products of the pulp and paper industry at time t-1 (i.e. lagged 1 period)	
	ϵ_t^{cz} : Disturbance stochastic term of the equation of price of consumption for the manufactured wood products of the pulp and paper industry at time t	

Source: Based on Martínez-Cortés (2023). The name of the variables and abbreviations of this table is found in the text. For a quick reference on them see Table 2. Notice that in Eq. 8, the MWfprw and MWNfrw markets are just a subdivision of the MWrw market by source of wood, and that the FWNfrw = FWrw market, as the only source of firewood considered in the current version of the CFSM is the natural forest.

MWrw: unprocessed wood for the manufactured wood products industry & final consumption other than firewood, FWrw: unprocessed wood for firewood, w: wood industry, f: furniture industry, z: pulp (Zellstoff in German) and paper industry, rw: unprocessed wood (or raw wood), MW: Manufactured wood products, WFP: Wood Forest Products, MWfprw: MWrw from forest plantations, MWNfrw: MWrw from natural forest, FWNfrw: FWrw from natural forest.

labor (L), capital (K) are specific to the domestic logging industry for forest plantations (i.e., for MWfprw) and natural forests (i.e., for MWNfrw) in the MWrw market, as well as for the natural forests in the FWrw market (i.e., for FWNfrw). Additionally, two other variables, VAST and GEN are included. VAST, representing the stock of wood available for supply at the beginning of year t, is only relevant in the MWfprw equation. GEN captures other costs of harvesting and those not captured by the L and K across the MWfprw, MWNfrw, and FWNfrw markets. Notably, FWrw is equivalent to FWNfrw due to the assumption that wood from forest plantations is used exclusively for industrial wood. Detailed explanations of VAST can be found in Appendix B.²

3.2.3. Demand-specific behavioral equations

3.2.3.1. Consumption (C). In the MWM, the Consumption (C) equations of its three individual markets (Eq. 9), incorporate not only the usual variables of price of consumption (PC) for the products w, f, and z, respectively, and income (Y), but also three additional macroeconomic variables: unemployment (U), inflation (i), and wealth (W). Consumption for specific manufactured wood products also depends on other

explanatory variables based on their use: products from the wood and furniture industries are durable goods, while products from the pulp and paper industry are non-durable goods (Kant et al., 1996). Consequently, the consumption for products manufactured by the wood industry for Colombia is mainly driven by the housing construction (HCS), which also influences demand for furniture; while population (N) impacts the demand for the non-durable goods produced by the pulp and paper industry.

For the UWM, equation consumption of the MWrw market (Eq. 10) is derived from the supply (production) of w, f, and z, (as determined by Eq. 8), along with the price of consumption for MWrw (PC^{MWrw}). For the individual market of FWrw, i.e., unprocessed wood for firewood, due to the informality of this market, we use a similar approach as in the literature on consumption patterns for firewood in other developing countries (FAO, 1994 and Fox, 1984), and model the consumption of FWrw (C^{FWrw}) as dependent on levels of income (Y), wealth W (as a determinant of substituting firewood with other sources of energy), geographic location (GEO), and population (in this research rural population NR is instead used as unprocessed wood for firewood is almost entirely used in rural areas in Colombia). Other independent variables, such as inflation (i) and unemployment (U) were also added to the consumption equation of the FWrw market (Eq. 10) for consistency with the explanatory variables used to explain consumption in the markets included in the MWM.

In the near future, current efforts from different Colombian government agencies are expected to provide more detailed information on the patterns of consumption of firewood in Colombia which might in turn require a future adjustment to the variables of the consumption equation of FWrw (Eq. 10).

² It's important to note that in the current version of the CFSM, VAST in Equation 8 of Table 1 (and in Equation 12, which is discussed later) refers exclusively to forest plantations, as this is the only wood source specified in detail in the version of the model presented here. Without changes in equation 8 (and in Eq. 12), this variable could be extended to include other sources of wood—such as natural forests, agroforestry systems, and trees outside forests—if historical data on changes in the areas and volumes, as well as growth and yield models for these sources become available.

3.2.3.2. Exports (X). In each of the five markets included in both (sub) models of the CFSM (i.e. MWM and UWM) — namely, w, f, z, MWrw, and FWrw markets — the main determinants of exports of the corresponding products are the prices of exported products, the Industrial Production Index (IPI) for each of the main importers of the exported products, country-specific exchange rates (RX) for importing countries, as well as any other variables that influence the consumption of the exported product, such as population and housing construction activity in the importing countries.

All exports in Colombia are traded in American Dollar (USD), and the pool of countries receiving Colombian exports, which include U.S., has evolved and could continue to change. Therefore, rather than relying on country-specific indexes, better explanatory variables of exports (X) equations in the individual markets of w, f, z, MWrw, and FWrw (Eq. 11) are the respective prices of exports (PX) for each product object of these markets relative to Colombia's USD exchange rate (RX), as well as the World's Industrial Production Index (IPI).

3.2.3.3. Imports (M). Colombia has a significant untapped capacity to produce unprocessed wood and manufactured wood products at competitive prices (Martínez-Cortés et al., 2022). As such, one of the motivations for developing the CFSM is to provide analytical advice on a sustainable development plan for capacity expansion, which, in turn, will lower imports and meet the increase demand of wood forest products stemming from a growing population and higher income levels. The Import (M) equations of w, f, z, MWrw, and FWrw markets (Eq. 12) include the usual explanatory variables that determine imports for the products object of these markets: the consumption expenditure (C), together with the relative price of consumption (PC) with respect to the price of imports (PM). For the MWM, imports equations of the w, f, and z markets, Colombia's capacity utilization rate for each industry producing w, f, and z is also included, respectively. In the UWM, the import equation for the MWrw market (Eq. 12) incorporates the CUR for Colombia's manufactured wood product industry as a whole, rather than for each specific industry, along with the volume available for supply (VAST) from forest plantations as an explanatory variable, the latter serving as a possible indicator of shortages in the national supply of national unprocessed wood for the manufactured wood products industry.³

Finally, it is worth noting that for the components of Demand in the CFSM, several factors affecting Consumption, Exports, and Imports of wood forest products, as mentioned in Section 2.3.2, were not included. This exclusion follows the same rationale explained at the beginning of Section 3.2.2 regarding the behavioral equations of Supply (Eq. 8).

3.2.4. Behavioral equations for prices of consumption (PC), of exports (PX), and of imports (PM)

The CFSM does not calculate a single prevailing price for supply and all demand components (consumption, exports, and imports). Instead, it computes the price of supply (PS) using the market clearing identities and includes separate price equations for each demand component (i.e., PC, PX, and PM) within the w, f, z, MWrw, and FWrw markets. This approach is supported by literature indicating that cross-border prices often deviate from the Law of One Price economic principle due to trade frictions (e.g., tariffs), differences in quality between domestic and foreign products, and imperfect substitution among aggregated items (Shahi et al., 2006; Olsson and Hillring, 2014). Consequently, the prices in both UWM and MWM are calculated with the assumption that domestic goods and foreign goods are not perfect substitutes, and as such,

³ For the behavioral equation of imports of the unprocessed wood for firewood market (M^{Fwrw}), the Capacity Utilization Rate (CUR) of the wood products industry and VAST are not considered main drivers and hence are excluded. This exclusion is represented by the case of $\beta_4^{mk} = \beta_5^{mk} = 0$ for $k = FWrw$, in equation 12 of Table 1.

resulting in different prices (i.e., PS, PC, PX, and PM) for different markets of the same products. In addition to the above assumption, the equations for calculating the demand component prices also consider the rigidity of prices, acknowledging that in the short run, industry prices are reluctant to adjust to changes in other economic factors such as output and demand, among others (Nakamura and Steinsson, 2013; Kant et al., 1996). To account for the reality of price responsiveness, the explanatory variables for each price equation also include lagged prices, a method widely established in forecast models of central banks, and also applied in Kant et al. (1996).

Therefore, the equations for the current price of consumption for each period t (PC_t) in the markets of w, f, z, MWrw, and FWrw (Eq. 13) include their corresponding closing price of the preceding time period (PC_{t-1}), along with the available supply (S) in each market, as determined by Eq. 8.

The price of exports (PX_t) equations in the markets w, f, z, MWrw, and FWrw markets incorporates the respective lagged price of exports (PX_{t-1}) for each product; the World Export Price Index (WEPI) for w, f, z, MWrw, and FWrw, correspondingly; and Colombia's USD exchange rate, as shown in Eq. 14.

Similar to the variables used by Kant et al. (1996), the price of imports (PM_t) for each of the five markets include as explanatory variables the previous period's import price (PM_{t-1}) for w, f, z, MWrw, and FWrw, respectively, the USD exchange rate for Colombia (RX), and the corresponding competing domestic consumption price (PC_t), derived in Eq. 13. Eq. 15 in Table 1 presents this relationship, concluding the theoretical structure and specification of the CFSM.

4. Methods and data for estimating and validating the Colombian forest sector model (CFSM)

4.1. Data collection and consolidation

To estimate the CFSM's theoretical behavioral equations presented in section 3, a comprehensive data collection and consolidation process was essential due to the decentralized nature of forest sector data (and certain economic data), a common challenge in tropical countries, including Colombia. This crucial step involved meticulously gathering, collecting, organizing, and transforming both historical and current data, which underpins the estimations and assumptions within the CFSM. This extensive effort led to the creation of Raw Data Tables, Transformation Tables, and Consolidated Data Tables for each equation of the CFSM, all carefully linked to their original sources. This approach ensures a transparent and systematic progression from raw data to the final model inputs, effectively addressing the transparency issues often associated with the complexity of FSMs, as highlighted by Toppinen and Kuuluvainen (2010).

Forest sector data scarcity in tropical countries, as noted by Haynes (1993), was mitigated by utilizing extensive data from the Supply and Use Tables (SUT) of Colombia's National Accounts, covering the period from 1970 to 2020. The quantities of supply (S), consumption (C), exports (X), and imports (M) for the five markets considered in the CFSM (w, f, z, MWrw, and FWrw), which are needed to represent the dependent variables, in the model's theoretical behavioral equations, were derived directly from the SUT. As is typical in tropical regions, Colombia lacks detailed price information for the markets considered in the FSM. To address this, we employed the methodology of Kant et al. (1996) to generate price deflators for these variables (i.e., PS, PC, PX, and PM) over the period 1970–2020. This was done by dividing the current monetary values of S, C, X, and M by their corresponding and constant monetary quantity for each market, providing a reliable measure of real price changes over time. For the independent variables in the model's theoretical equations, we utilized a diverse range of data sources including digital and paper-format publications from Colombia's National Statistics System and other public and private sources (e.g., DANE's Manufacturing Annual Survey, Colombia's Central Bank data

repositories, Fedesarrollo's Enterprise/Industrial Opinion Survey) as well as international databases like FAO, World Bank, and FRED, supplemented by relevant forest sector literature.

For the variables in the CFSM's theoretical equations where raw data were either unavailable or not directly accessible, comprehensive data estimations were undertaken. This included estimating S, C, X, and M for MWrw and FWrw markets from 1970 to 1993, as well as 1970–2018 estimations for S at purchaser prices, Colombia's wealth (W), and asset values (i.e., the Capital (K) variable) for the w, f, and z industries, as well as the Capacity Utilization Rate (CUR) of these industries for specific years. A detailed approach was used for each estimation, such as segregating data from aggregated forestry sources and adjusting values based on different economic models. This comprehensive estimation process also included generating data for the Total Volume of Available Stock (VAST) of unprocessed wood from forest plantations which extended to the period 1954 to 2019 using various sources and methods, and the annual volume harvested (VH, see Appendix B), legal and illegal, from all national sources of wood.

Despite these efforts, obtaining complete data for all variables of the CFSM's theoretical equations presented in section 3 and summarized in Table 1 was not always possible. Where data was missing, proxy variables were utilized as substitutes. Consequently, some variables, such as labor (L) and capital (K) for the logging industry of commercial forest plantations for the MWfprw market, and K for the logging industry of natural forest in the MWnfrw and FWnfrw markets, as well as others capturing various costs (GEN) and geographical locations (GEO), all them part of Equations of Supply (Eq. 8) in the sub-model named UWM, had to be omitted due to the lack of direct data or suitable proxies. Additionally, between 1970 and 2018, Colombia's export and import of unprocessed wood for firewood (FWrw) were either nonexistent or so negligible that they were not recorded as nonzero values in the SUT. Hence, this led to the exclusion of the FWrw market from the CFSM's import and export equations, as well as from their corresponding price equations.

Following the detailed data estimation efforts for the CFSM, the next phase involved selecting the most representative time series for each theoretical equation from the raw data tables and then applying necessary transformations to complete the data consolidation process. These transformations included standardizing units, adjusting base years, scaling, normalizing variables to ensure time series stationarity. Additionally, they included converting absolute prices to relative prices to address the common issue of incorrect coefficient signs for absolute prices during the estimation process.

Monetary values were converted to thousands of millions of Colombian Pesos (COP) and standardized to the 2015 base year. Additionally, constant prices for 2015 were applied where necessary. The method of geometric interpolation in reverse for current prices and variation rate method for constant values was used to link time series across different base years, ensuring the values' integrity and consistency (DANE, 2013, 2020). Indexes and deflators were also rescaled to the 2015 base year. Specific variables, such as Consumption (C) and Wealth (W), were normalized against Colombia's total income (Y), while variables like Housing Construction (HCS), Population (N), and Rural Population (NR) were normalized using Colombia's Number of Households (NHH). The absolute consumption price (PC) for w, f, z, MWrw, and FWrw was converted to relative price using several variables, including the contemporary and lagged Consumer Price Index of Colombia (PC_{t-1}^{Col} and PC_t^{Col}), the Price of Housing (Ph), and the Price of Housing Construction Materials (P^{hcm}), as well as the imports price (PM) and its own lagged price (PC_{t-1}). Finally, the absolute price of exports (PX) was converted to a relative price by dividing it by Colombia's USD exchange rate (RX).

These transformations, crucial for the accuracy and relevance of the model, were comprehensively organized, along with the consolidated data (time series) used for estimation, for each variable in the Transformation and Consolidated Tables of every equation of the CFSM. For

the most part, consolidated data covered the period 1970–2018 (49 years), but the time series used for estimating the theoretical equation parameters in both sub-models (MWM and UWM) of the CFSM only covered 1975–2015 (41 years). Data from the years after 2015 was reserved for the out-of-sample validation process.

Table 2 summarizes all variables from the CFSM's theoretical behavioral equations (Table 1) for which at least one complete 1970–2018 time series could be consolidated for parameter estimation and model validation. It also includes the price variables used to convert the absolute prices to relative prices, some of which were not included in Table 1. For each of these variables, the table provides their superscripts, a description of the available consolidated time series representing the variable, their sources, and the corresponding units.

Note that for several CFSM variables, the notation consists of the variable abbreviation (column 1 of Table 2) and its superscript (column 3 of Table 2). A general form of this notation was previously used in Table 1, while its specific form will be used throughout the remainder of the paper, starting in the following subsection. For clarification, consider the Supply (S) equation (Eq. 8 in Table 1), where the dependent variables are defined as S^k applicable to all individual smallest-scale markets included in the CFSM, namely w, f, z, MWrw (and its subdivisions MWfprw and MWnfrw) and FWrw (equal to FWnfrw). The equivalent variable in Table 2 appears in rows where S is listed in the first column. This abbreviation applies to the same markets, as indicated in column 3. Hence, the first row for S represents five variables: S^w , S^f , S^z , S^{MWrw} , and S^{FWrw} , while the second row accounts for three variables: S^{MWfprw} , S^{MWnfrw} , and S^{FWfprw} . We chose to present the CFSM's variables in more mathematical notation in Table 1 and a more concise manner in Table 2 to avoid repetition and save space in the paper.

4.2. Parameter estimation of behavioral equations of the CFSM

Ordinary Least Square (OLS) was used for the parameter estimation of the theoretical behavioral equations in Table 1 for the three individual markets under the MWM submodel (w, f, and z) and the two individual markets under the UWM submodel (MWrw, including its subdivisions MWfprw and MWnfrw, and FWrw, which is equal to FWnfrw). In total, 32 behavioral equations were estimated for the CFSM — 21 for the MWM and 11 equations for UWM. The estimated equations included the Supply equations for MWfprw and MWnfrw (as only supply equations were considered for these divisions of the MWrw market) and excluded the Imports and Exports equations for FWrw, along with their corresponding prices, due to the unavailability of consolidated time series data, as discussed in the previous subsection. The estimations were conducted using IBM SPSS Statistics® 26.

The parameter estimation and selection of the final estimated equations process closely followed the methodology described by Kant et al. (1996, p. 1123), and included: 1) testing the set of the variables of choice for each theoretical behavioral equation to achieve final estimated equations in compliance with the statistical and economic requirements for the model; 2) reviewing the assumptions underlying the OLS estimate, for statistical inferences about the estimated parameters, such as their precision and validity, as well as detecting and, when possible, correcting any issues related to the non-normality, heteroscedasticity, multicollinearity, and serial correlation of the disturbance term; 3) finally, checking for first-order autocorrelation by using the Durbin Watson d (DW d) statistic. For equations with lagged variables, Durbin h (Dh) statistic was applied, instead of DW d. In cases where the estimated DW d fell in the inconclusive zone of evidence of autocorrelation or Dh was not computable, Graph methods (partial autocorrelogram), the Run test, and the Breusch–Godfrey were used.⁴ If subject to first-order autocorrelation, it was addressed by using Prais-

⁴ For a heuristic explanation on how tests for detecting first-order serial correlation work, see Gujarati and Dawn (2009).

Table 2
List of variables, available time series, sources and units used for the CFSM.

Variable abbreviation	Name of original (or proxy) variable	Variable superscript (group of products or market)	Consolidated annual time series that could represent the variable (1970–2018)	Units of the consolidated data	Sources of Data*
C	Consumption	w, z, FWrw, MWrw f	Intermediate + Final consumption at purchaser's prices Intermediate + Final consumption + Gross Fixed Capital Formation (GFKF) at purchaser's prices	2015 Thousand million COP	1
CT	Total consumption	rw, MW, WFP	Sum of the series of C for their corresponding individual/aggregated markets		2
CUR	Capacity utilization rate	w, z, f, MW	Capacity utilization rate	Percentage	3
D	Demand	w, z, f, MWrw, FWrw	Demand at purchaser's prices	2015 thousand of million	1
DT	Total demand	rw, MW, WFP	Sum of the series of D for their corresponding individual/aggregated markets	COP	2
HCS	Housing construction starts (Approved area for housing construction as proxy for HCS)		Approved area for housing construction	Thousands of square meters approved for construction	4
i	Inflation		Consumer price index	Percentage	5
IPI	Global Industrial Production Index (US IPI as proxy for Global IPI)		US Industrial Production Index, Annual, Seasonally Adjusted		6
IPP	Producer price index. Total for Agriculture, Forestry, livestock and fishing		Producer price index. Total for Agriculture, Forestry, livestock and fishing	Unitless, 2015 = 1	7
K	Capital (of each industry in the Annual Manufacturing Survey, MAS)	w, f, z	Value of Machinery and Equipment + Building and Structures, at 31st of December	2015 Thousand million COP	2, 8
L	Labor (of each industry in the MAS)	w, f, z	Employment	Number (of people employed)	8
L	Labor (NR as proxy for Labor of the logging industry for natural forest)	MWnfrw, FWnfrw	Rural population as proxy for Employment	Number (of people)	5
M	Imports	w, z, f, MWrw, FWrw	Imports at purchaser's prices	2015 Thousand million COP	1
MT	Total imports	MW, rw, WFP	Sum of the series of M for their corresponding individual/aggregated markets		2
N	Total Population		Total population (midyear estimates)		5
NHH	Households		Households	Thousands	9
NR	Rural population		Rural population		5
PC	Consumption price	w, z, FWrw, MWrw f	Consumption price deflator (Weighted average for Intermediate and Final consumption) = Consumption in current values / Consumption in constant values Consumption price deflator (Weighted average for Intermediate, Final consumption and Gross Fixed Capital Formation) = Consumption in current values / Consumption in constant values		10
PC ^{Col}	Consumer's price index		Consumer price index	Unitless, 2015 = 1	11
p ^h	Price of housing		Used housing price index		12
p ^{hcm}	Price of housing construction materials		Producer price index by economic destination or use: Construction materials		12
PM	Import price	w, f, z, MWrw, FWrw	Import price deflator = Imports in current values / Imports in constant values		10
PS	Supply price	w, f, z, MWrw, FWrw	Supply price deflator = Supply in current values / Supply in constant values		10
PX	Export price	w, f, z, MWrw	Export price deflator = Exports in current values / Exports in constant values		10
RX	Exchange rate		Official exchange rate (UMN per US\$, average for a period) or Exchange rate, national currency (COP)/USD (market+estimated)	COP/USD	6
S	Supply	w, f, z, MWrw, FWrw	Gross production at purchaser's prices	2015 Thousand million COP	1
S	Supply	MWfprw, MWnfrw	Gross production at purchaser's prices for MWrw, weighted by the production quantity (in physical volume) of unprocessed wood by source		2
S	Supply*	MWrw, FWrw	Production quantity	Million cubic meters of under bark roundwood	13
ST	Total supply	MW, rw, WFP	Sum of the series of S for their corresponding individual/aggregated markets	2015 Thousand million COP	2
U	Unemployment		Overall unemployment rate (average of each year)	Percentage	14

(continued on next page)

Table 2 (continued)

Variable abbreviation	Name of original (or proxy) variable	Variable superscript (group of products or market)	Consolidated annual time series that could represent the variable (1970–2018)	Units of the consolidated data	Sources of Data*
VAST	Total Volume of available stock of unprocessed wood for Supply at the beginning of a year	MWrw (MWfprw+MWnfrw), FWRw	Volume of available Stock [(unprocessed) wood] for Supply at the beginning of a year after discounting VH from the last year	Million cubic meters of under bark roundwood	15, 16, 17
W	Wealth	w	Estimated wealth = Capital stock + Public debt - External debt	2015 Thousand million COP	18
WEPI	World Exports price Index (US Producer Price Index by Commodity as proxy for Global WEPI)	f	US Producer Price Index by Commodity for Furniture and Household Durables; Household Furniture	Unitless, 2015 = 1	6
X	Exports	z	US Producer Price Index by Commodity for Pulp, Paper, and Allied Products		1
XT	Total exports	w, z, f, MWrw, FWRw	Exports at purchaser's prices		2
Y	Total income	MW, rw, WFP	Sum of the series of X for their corresponding individual/aggregated markets	2015 Thousand million COP	5

Source: Modified from Martínez-Cortés (2023).

MWrw: unprocessed wood for the manufactured wood products industry & final consumption other than firewood, FWRw: unprocessed wood for firewood, w: wood industry, f: furniture industry, z: pulp (Zellstoff in German) and paper industry, rw: unprocessed wood (or raw wood), MW: Manufactured wood products, WFP: Wood Forest Products, MWfprw: unprocessed wood for the manufactured wood products industry & final consumption other than firewood from forest plantations, MWnfrw: unprocessed wood for the manufactured wood products industry & final consumption other than firewood from natural forest. In the CFSM it was assumed that FWRw is only supplied from natural forests (nf), hence FWRw = FWNfrw, where FWNfrw: unprocessed wood for firewood from natural forest, fp reads as forest plantations. All variables listed refer to Colombia unless otherwise specified. * The supply in physical quantities is only used to separate the Supply in monetary values coming from that of forest plantations and to estimate the variable VAST. In the estimated equations only supply in monetary values is used.

For the references listed in sources of data of this table, see Appendix D.

Winsten (PW) and Cochrane-Orcutt (CO) methods.

Lastly, obtaining signs of variables in accordance with economic theory and no first-order autocorrelation were the main criteria for selecting a final equation. For choosing among equations with alternative specifications (including those resulting from variables with more than one time series available), the additional conditions used in selecting the final equation were the adjusted-R² and statistical significance of individual variables. When first-order correlation was not corrected by applying PW and CO methods, the OLS equation was retained for the model. In our model, similar to other models (including FSMs), the finally selected estimated equations are the result of “considerable specification searching, and classical interpretations of econometrics may not fully apply” (Kant et al., 1996, p. 1123). The details of the process of estimation and the final inclusion of each equation are available in Martínez-Cortés (2023).

4.3. Model validation

The CFSM validation involved the comparison between the values of all endogenous variables predicted by CFSM and their actual values, which allows for knowing “the magnitude of forecasting error that may result from using the model” (Haitovisky et al., 1974). To assess the forecasting error, we used Theil’s inequality coefficients U₁ (Theil, 1958) and U₂ (Theil, 1966), both relative measures of the root mean squared error (rmse), as well as their decomposition into the proportions of the bias (U^m), variance (U^s), and covariance (U^c). We also utilized the correlation coefficient (R) between forecasted and actual values, as per Kant et al. (1996).

For producing the predicted values needed to validate the model, we developed a *CFSM-I App*, a software application built in Excel® using Visual Basic for Applications to solve and use the CFSM. By running this app, whose features allow easily to validate, use, and update one, several or the total variables, equations, and markets of the CFSM, several simulations were executed to validate every individual equation in three contexts: each equation in isolation, in making part of each PEM representing the w, f, z, MWrw, and FWRw when each of these market work independently from the others, and in the same case but when those markets work connected. This latter represents the wood forest product market (WFP) as an aggregated.

For the last two simulations, a non-clearing and clearing situation of the markets were tested. In this case, all PEMs representing the five markets that make up the aggregated market of WFP have their connecting variables (S^w, S^f, S^z and PC^{MWrw} and PS^{MWrw}) “active”.⁵ This means that interactions are allowed between PEMs, and as such, for any particular year, solutions are simultaneously found in all five PEMs, the sub-models UMW and MWM, and the aggregated model (CFSM, corresponding to the WFP market). To allow that, model summation and market clearing identities are used in addition to the behavioral estimated equations for the CFSM for the MCC case, while ST_t = DT_t as well as the individual market clearing identities are absent in the Non-MCC case. To find the MCC (i.e., to solve the model) the *CFSM-I App* uses the primal Simplex⁶ and the Generalized Reduced Gradient (GRG Non-linear)⁷ methods which are already part of the add-on modules in

⁵ The reader can see the connecting variable among PEMs as follows: PC^{MWrw} as a normalized independent variable in the Supply Equations 8.1, 8.2, and 8.3 (Table 3); S^w, S^f, S^z as independent variables in the Consumption Equation of MWrw (Eq. 10.1) and PS^{MWrw} as normalizing variable in the Supply Equation of FWRw (Eq. 8.6).

⁶ Based on the Simplex Method “originally developed by Dantzig in 1948” (<https://www.solver.com/linear-quadratic-programming> accessed on August 19, 2022)

⁷ As implemented in an enhanced version of Lasdon and Waren’s GRG2 code (<https://www.solver.com/smooth-nonlinear-technology> accessed on August 19, 2022)

Microsoft Excel Solver®.

As Colombian market of unprocessed wood for firewood, FWrw, is in general quite different to that of the Colombian market of unprocessed wood for the manufactured wood products and final consumption other than firewood (MWrw), and since the former is weakly linked to the other four markets modeled, the validation for the CFSM was also done without considering the FWrw market (i.e., “turning off” the partial equilibrium model for FWrw).

In the last step of the validation process, as per Pindyck and Rubinfeld (1998), the CFSM was simulated subject to both larger changes in exogenous variables or policy parameters (stimuli), and changes in the year the simulation starts. We tested the exogenous variables VAST, K, and HCS, as well as the alternative starting years: 1982 and 2002. Additional information on CFSM validation, as well as the other aspects of the methods and data discussed in this section, is provided in Martínez-Cortés (2023).

Finally, we aimed to extensively benchmark our CFSM estimation and validation against existing literature. However, this paper is the first to estimate parameters of behavioral equations for Colombia’s wood forest products markets and to validate their reliability and stability within a forest sector model, leaving us without direct prior studies for direct comparison. Nonetheless, we incorporate published results from other regions and methodologies to facilitate some indirect and limited comparative analysis.

5. Results of the CFSM estimation and validation

5.1. Final estimated behavioral equations of the CFSM

The results from estimating the 32 behavioral equations included in both sub-models of the CFSM—21 in the MWM and 11 in the UWM—are presented in Tables 3 and 4. Table 3 covers all the equations for the markets of manufactured wood products of the wood industry (w), furniture industry (f), and pulp and paper industry (z). Table 4 contains all the equations for the markets of unprocessed wood for the manufactured wood products industry and final consumption other than firewood (MWrw) and of unprocessed wood for firewood (FWrw).

Note that these tables do not include the identities for five markets mentioned above, nor the identities for the two aggregated markets—manufactured wood products (MW) and unprocessed wood (UW or rw)—or the total market for wood forest products (WFP), numbered 1 to 7 in Table 1, as these do not undergo the estimation process.⁸ Consequently, the numbering of the market-specific estimated behavioral equations presented in Tables 3 and 4 starts from Eq. 8.1 and 8.4, respectively, to maintain consistency with the general theoretical behavioral equations presented in Table 1 from which they were derived. For instance, the supply equations in Table 3 and Table 4 are numbered 8.1, 8.2, 8.3 and 8.4, 8.5, 8.6, respectively, as they are derived from Eq. 8 in Table 1, following the variable inclusion/exclusion rules specified there. It is also worth noting that some variables appearing in the general theoretical behavioral equations in Table 1 may be omitted in the corresponding specific estimated equations of Tables 3 and 4, while others may be presented in normalized or relative terms (e.g., C_t^{MWrw}/Y_t in Eq. 10.1 of Table 4 and PC_t^{MWrw}/p_t^{hcm} in Eq. 8.1 of Table 3). The use of normalized or relative terms as shown in Tables 3 and 4, rather than the non-normalized and absolute forms presented in Table 1, was intended to produce superior estimated equations—a common practice in econometrics (Kallio et al., 1987; Buongiorno, 1996; Ferrer Velasco et al., 2020).

For a better interpretation, in addition to the final estimated

⁸ Readers interested in the specific identities for each individual, aggregated, and total markets, which, together with the behavioral estimated equations in Tables 3 and 4, complete all the PEMs of the CFSM, can refer to Martínez-Cortés (2023).

behavioral (regression) equations, Tables 3 and 4 include the values of the t statistic, t statistic with robust standard errors (for OLS estimation), adjusted R², DW d or Dh (acceptable values between −1.64 and +1.64), rho (ρ) coefficient of first-order autocorrelation with t statistic on the right, and the standard error of the estimate divided by the mean of the dependent variable (SEE/MDV).

5.1.1. Supply-side equations

During the estimation of Supply (S) equations, several challenges were encountered and mostly resolved. Initial OLS regression equations for supply for all products considered, with the exception of the S^{FWnrw} which had an adjusted-R² of 0.39, generally demonstrated a good fit (adjusted-R² ranging from 0.77 to 0.99). Despite this, the OLS estimation produced some coefficients with signs contrary to economic theory, and, except for the estimates of the S^f , all coefficients were subject to first-order autocorrelation of the disturbances (autocorrelation hereafter). Subsequent re-estimations using CO and PW methods corrected the autocorrelation and most incorrect signs. However, some coefficients continued to display incorrect signs even after these corrections. Specifically, wrong signs persisted for the coefficients of the consumption price of MWrw (PC^{MWrw}) in the equations for S^w , S^f and S^z , as well as for the coefficients of the supply price of FWrw (PS^{FWrw}) and the proxy variable for Labor, rural population (NR), used in the equation of Supply of FWrw from natural forest (S^{FWnrw}), as well as for the coefficient of capital of w (K^w) in the equation of S^w .

The issue of obtaining incorrect signs for econometric estimations of price parameters in forestry has been reported by several authors, including Singh and Nautiyal (1986), Haynes (1993), Kant et al. (1996), and Jeuck et al. (2014). To address the issue of incorrect signs for price parameters, this research adopted an approach similar to that of Kant et al. (1996) by using relative prices rather than absolute prices. Specifically, the ratio of PC^{MWrw} to price of housing construction materials (Ph^{cm}) was used in the equation of S^w (Eq. 8.1) while the ratio of PC^{MWrw} to price of housing (Ph) was applied in equations of S^f and S^z (Eq. 8.2 and 8.3). For the equation of S^{FWnrw} (Eq. 8.6) the ratio of PS^{FWrw} to the price of supply of MWrw (PS^{MWrw}) was tried. These relative prices resulted in price coefficients with the correct signs, without affecting the correct signs of the other variable coefficients obtained by the first OLS (for S^f), CO (for S^z , S^{MWrw} and S^{FWnrw}) and PW (for S^{MWrw}) estimates.

However, these new estimations did not correct the incorrect signs for the coefficients of both NR (in the equation of S^{FWnrw}) and K^w and PC^{MWrw} (in the equation of S^w). A new estimation for S^{FWnrw} was performed using the variable NR normalized by total population (N), resulting in an equation free of autocorrelation, with all the correct signs and the normalized variable highly significant (as shown in Eq. 8.6 of Table 4). None of the multiple tries of applying OLS, CO, and PW methods, which included using other six times series available to represent K^w (in addition to the one showed in Table 2 for this variable) gave an equation for S^w with coefficient of K^w showing the expected sign (positive). As a result, the K^w was dropped in that equation, as can be seen in Eq. 8.1 of Table 3. In this equation we retain the variable PC^{MWrw}/p^{hcm} (whose coefficient had a correct sign but was non-significant) because of matters of replicability of the variation and good tracking of the actual data series.

All coefficients of the final estimated supply equations selected for being part of both the MWM and UWM (Eq. 8.–1 to 8.6), have the correct signs—consistent with economic theory—and most of them are significantly different from zero. The coefficient of the VAST (a key policy variable of the CFSM) for S^{MWrw} (Eq. 8.–4) was statistically significant and different from zero but at a 15 % level of significance. The coefficient of the PS in all equations was also different from zero, at levels of significance of 5 % in the equation of S^{MWrw} and in that of S^w , and at 1 % in equations of S^f , S^z , and S^{MWrw} . In the supply equations for the f and z industries, the coefficients of capital (K) and labor (L) were also statistically significant and different from zero at levels <7.5 %. Finally, the coefficient for the proxy variable of labor (i.e., NR/N) used

Table 3
Final Estimated Behavioral Equations for the MWM of the CFSM.

Equation number	Equation name	Method of estimation	Description	Estimated Equation											
8.1	Supply (Production) of manufactured wood products of the wood industry	AR(1) CO - Cochrane-Orcutt method	Regression Equation t statistics	$S_t^w = 2248.7461326 + 1741.0367355 PS_t^w + 0.0066841 L_t^w - 8816.7016208 PC_t^{MWRw}/P_t^{hcm} - 0.2$	2.5	2.2	0.2	-	14.0	8.4%					
				Adj. R ² = 0.03	DW d = 1.7										
8.2	Supply (Production) of manufactured wood products of the furniture industry	OLS - Ordinary least squares	Regression Equation t statistics t statistics with robust standard errors	$S_t^f = 17.9182170 + 4865.4819046 PS_t^f + 0.0793323 L_t^f + 0.3334932 K_t^f - 430.913581 PC_t^{MWRw}/P_t^h$	0.2	11.3	5.3	3.2	-1.8						
				Adj. R ² = 0.99	DW d = 1.7										
8.3	Supply (Production) of manufactured wood products of the pulp and paper industry	AR(1) CO - Cochrane-Orcutt method	Regression Equation t statistics	$S_t^p = 3870.9075320 + 7358.1621388 PS_t^p + 0.0947103 L_t^p + 0.5908341 K_t^p - 2179.3166 PC_t^{MWRw}/P_t^h - 1.9$	3.9	3.7	1.8	+	10.2	5.4%					
				Adj. R ² = 0.70	DW d = 1.1										
9.1	Consumption of manufactured wood products of the wood industry	AR(1) PW - Prais-Winsten method	Regression Equation t statistics	$C_t^w / Y_t = 0.00754967 - 0.09352710 PC_t^w / P_t^{hcm} - 0.00009993 U_t + 0.00000075 HCS_t / NHH_t$	4.0	-0.6	-1.6	+	12.9	8.2%					
				Adj. R ² = 0.07	DW d = 1.9										
9.2	Consumption of manufactured wood products of the furniture industry	AR(1) PW - Prais-Winsten method	Regression Equation t statistics	$C_t^f / Y_t = 0.009505153 - 0.114112642 PC_t^f / P_t^{hcm} - 0.000101239 U_t + 0.000000769 HCS_t / NHH_t$	3.6	-0.7	-1.4	+	18	8.1%					
				Adj. R ² = 0.06	DW d = 1.3										
9.3	Consumption of manufactured wood products of the pulp and paper industry	AR(1) PW - Prais-Winsten method	Regression Equation t statistics	$C_t^p / Y_t = 0.01381023 - 0.54708842 PC_t^p / PC_t^{col} - 0.00011820 U_t + 0.00374694 N_t / NHH_t$	1.2	-1.8	-0.7	+	18.6	5.9%					
				Adj. R ² = 0.00	DW d = 1.8										
11.1	Exports of manufactured wood products of the wood industry	AR(1) CO - Cochrane-Orcutt method	Regression Equation t statistics	$X_t^w = -47.2232115 + 142.4008357 IP_t + -22739.3863258 PX_t^w / RX_t$	-1.1	3.5	-0.8	-	5.13	36.3%					
				Adj. R ² = 0.29	DW d = 1.4										
11.2	Exports of manufactured wood products of the furniture industry	AR(1) CO - Cochrane-Orcutt method	Regression Equation t statistics	$X_t^f = -94.7349542 + 515.2883424 IP_t - 375985.6483349 PX_t^f / RX_t$	-0.6	2.6	-2.7	-	6.64	38.5%					
				Adj. R ² = 0.19	DW d = 2.1										
11.3	Exports of manufactured wood products of the pulp and paper industry	AR(1) PW - Prais-Winsten method	Regression Equation t statistics	$X_t^p = -41.3144894 + 695.3970228 IP_t + 551501.3181275 PX_t^p / RX_t$	-0.1	1.3	0.7	+	18.4	20.7%					
				Adj. R ² = -0.01	DW d = 1.4										
12.1	Imports of manufactured wood products of the wood industry	AR(1) PW - Prais-Winsten method	Regression Equation t statistics t statistics with robust standard errors	$M_t^w = -85.89613705 + 0.09839081 C_t^w + 302.75348214 PC_t^w / PM_t^w - 0.44302215 CUR_t^w$	-0.6	2.6	2.4	-	17.5	25.1%					
				Adj. R ² = 0.39	DW d = 1.3										
12.2	Imports of manufactured wood products of the furniture industry	AR(1) PW - Prais-Winsten method	Regression Equation t statistics	$M_t^f = 216.40363890 + 0.13100586 C_t^f + 91.01801982 PC_t^f / PM_t^f$	-1.7	5.7	1.6	-	19.1	19.9%					
				Adj. R ² = 0.50	DW d = 1.9										
12.3	Imports of manufactured wood products of the pulp and paper industry	AR(1) PW - Prais-Winsten method	Regression Equation t statistics	$M_t^p = -770.1213975 + 0.2335422 C_t^p + 923.8895191 PC_t^p / PM_t^p - 5.8249830 CUR_t^p$	-1.9	18.2	4.6	-	4.91	7.4%					
				Adj. R ² = 0.89	DW d = 1.4										
13.1	Consumption price of manufactured wood products of the wood industry	OLS - Ordinary least squares	Regression Equation t statistics t statistics with robust standard errors	$PC_t^w / PC_t^{col} = 0.0021974 - 0.000000016 S_t^w + 0.8330429 PC_{t-1}^w / PC_{t-1}^{col}$	2.4	-2.0	11.3	+		4.7%					
				Adj. R ² = 0.83	Dh = 2.0										
13.2	Consumption price of manufactured wood products of the furniture industry	OLS - Ordinary least squares	Regression Equation t statistics t statistics with robust standard errors	$PC_t^f / P_t^{hcm} = 0.0014464411 - 0.0000000803 S_t^f + 0.8957963334 PC_{t-1}^f / P_{t-1}^{hcm}$	1.7	-1.6	12.1	+		5.5%					
				Adj. R ² = 0.79	Dh = -1.2										
13.3	Consumption price of manufactured wood products of the pulp and paper industry	OLS - Ordinary least squares	Regression Equation t statistics t statistics with robust standard errors	$PC_t^p / PC_t^{col} = 0.005378794 - 0.000000183 S_t^p + 0.672400253 PC_{t-1}^p / PC_{t-1}^{col}$	3.6	-2.8	8.3	+		5.3%					
				Adj. R ² = 0.92	Dh = 0.6										
14.1	Export price of manufactured wood products of the wood industry	AR(1) PW - Prais-Winsten method	Regression Equation t statistics	$PX_t^w = -0.01795662 + 0.36690977 PX_{t-1}^w + 0.00025066 RX_t + 0.10977207 WEPI_t^w$	-0.3	3.7	6.0	+	1.94	8.5%					
				Adj. R ² = 0.98	Dh = 1.2										
14.2	Export price of manufactured wood products of the furniture industry	OLS - Ordinary least squares	Regression Equation t statistics t statistics with robust standard errors	$PX_t^f = -0.17124469 + 0.67176581 PX_{t-1}^f + 0.00002664 RX_t + 0.40915616 WEPI_t^f$	-2.5	4.6	1.1	+		13.3%					
				Adj. R ² = 0.97	Dh = 2.7										
14.3	Export price of manufactured wood products of the pulp and paper industry	OLS - Ordinary least squares	Regression Equation t statistics t statistics with robust standard errors	$PX_t^p = -0.101249006 + 0.048753909 PX_{t-1}^p + 0.000281241 RX_t + 0.264386451 WEPI_t^p$	-5.7	0.7	12.9	+		5.6%					
				Adj. R ² = 1.00	Dh = 5.0										
15.1	Import price of manufactured wood products of the wood industry	AR(1) CO - Cochrane-Orcutt method	Regression Equation t statistics	$PM_t^w = 0.0245559762 + 0.5326640749 PM_{t-1}^w + 0.0307631699 PC_t^w / PC_{t-1}^w + 0.0001605137 RX_t$	0.2	5.1	0.27	+	3.2	9.3%					
				Adj. R ² = 0.931	Dh = 0.91										
15.2	Import price of manufactured wood products of the furniture industry	AR(1) CO - Cochrane-Orcutt method	Regression Equation t statistics	$PM_t^f = -0.018876658 + 0.537659381 PM_{t-1}^f + 0.010719018 PC_t^f / PC_{t-1}^f + 0.000193668 RX_t$	-0.3	10.8	0.2	+	3.6	4.9%					
				Adj. R ² = 0.987	Dh = 0.89										
15.3	Import price of manufactured wood products of the pulp and paper industry	AR(1) PW - Prais-Winsten method	Regression Equation t statistics	$PM_t^p = -0.09146760 + 0.37663883 PM_{t-1}^p + 0.07214532 PC_t^p / PC_{t-1}^p + 0.00022556 RX_t$	-1.1	3.8	1.12	+	7.2	8.3%					
				Adj. R ² = 0.907	Dh = 1.11										

Source: Martínez-Cortés (2023).

in the equation of supply of unprocessed wood for firewood (S^{FWnfrw}) was different from zero at a level of significance of 0.1 %. The coefficients that were not different from zero even at 15 % significance level included labor for the wood industry (L^w) and relative consumption price of unprocessed wood (PC^{MWRw}/P^{hcm}) in the equation of S^w , rural population (NR) in the equation of S^{MWRw} , and the relative supply price of unprocessed wood for firewood (PS^{FWnfrw}/PS^{MWRw}) in the

equation of S^{FWnfrw} .

Similar results for the signs and significance of parameters in the behavioral equations for S^f and S^p were found by Kant et al. (1996), the most directly comparable study found in academic literature. This is noteworthy given the warning from Turner and Buongiorno (2004) about comparing econometric estimates: "results of previous studies are difficult to compare because of differences in product definition, data

sources, period covered, model form, and estimation methods". A deviation from Kant et al.'s findings is observed in our estimated equation for the supply of manufactured wood products (S^w). While Kant et al. (1996) found that all three variables they include as explanatories— PS^w , L^w , and K^w —were significant and had positive signs, our equation has only the first variable, PS^w , with the correct sign and significance. The second variable, L^w has the correct sign but is non-significant, and the third variable, K^w , was excluded due to an incorrect sign.

These contradictory results may be attributed to differences between the Canadian forest industry (modeled by Kant et al.) and the Colombian industry. In Colombia, there have been no significant new investment initiatives to expand the installed production capacity of manufactured wood products since the 1970s (Martínez-Cortés and Kant, 2024). Consequently, the industry may have been operating close to the maximum level of labor needed to utilize its existing capital—comprising machinery, equipment, and structures, much of which was already depreciated decades ago—throughout most of the years between 1975 and 2015. This lack of variation in the time series data for labor and capital used to estimate our S^w equation might have contributed to the non-significant results for labor and the unexpected sign for capital. Additionally, data quality and measurement errors, particularly given the substantial number of small establishments in the wood industry, could also have distorted the relationships between these variables and their expected effects.

Finally, it is worth mentioning that the results of the coefficients for the rest of the variables in the supply equations align with the findings reported by McKillop (1967), Buongiorno et al. (2003b), Daigneault et al. (2016), Borzykowski (2019), and Buongiorno and Zhu (2020) in terms of signs and significance across different geographical contexts, though direct comparisons for Colombia are inherently limited by the aforementioned restrictions cited from Turner and Buongiorno (2004).

5.1.2. Demand-side equations

5.1.2.1. Consumption. To obtain the final estimated consumption equations presented in Tables 3 and 4 (Eq. 9.1, 9.2, 9.3, 10.1, and 10.2), normalized variables were necessary to ensure stationarity in time series data, and relative prices were used to achieve correct coefficient signs. In all five equations, the dependent variable of consumption (C) was normalized by total gross disposable income (Y), as per Kant et al. (1996). Y was also used to normalize supply variables (S^w , S^f , and S^z) in the derived consumption equation for MWRw (C^{MWRw} , Eq. 10.2). The number of households (NHH) was selected to normalize housing construction starts (HCS), total population (N), and rural population (NR) in the equations for C^w , C^f , C^z , and C^{MWRw} . Additionally, P^{hcm} was used to convert the absolute PC of the respective products to relative terms in the equations for C^w , C^f , and C^{MWRw} , while Colombia's consumer price index (PC^{Col}) was employed in the equation for C^z . Problems with incorrect signs of estimated coefficients for PC in consumption equations were also found by Kant et al. (1996) and Singh and Nautiyal (1986), with Kant et al. identifying PC as one of the most troublesome variables in forest products consumption estimates. Initial OLS estimates for the five consumption equations, using normalized and relative variables, exhibited autocorrelation. Consequently, all estimates required autocorrelation correction.

In all five consumption estimated equations presented in Tables 3 and 4, which are free of autocorrelation, the signs of the coefficients agree with those expected by economic theory, though their significance levels vary widely. Prices of consumption in equation of C^z (Eq. 9.3) and C^{FWrw} (Eq. 10.2) were different from zero at 7.5 % and 0.1 % levels of significance, respectively, but for the remaining three equations (C^w , C^f , and C^{MWRw} , Eq. 9.1, 9.2, and 10.1, respectively), they were statistically significant from zero only at more than 15 % significance levels. The coefficients of HCS/NHH and U were different from zero at the 15 % and

10 % levels of significance in equations of C^f and C^w , respectively. Interestingly, the coefficient of S^w/Y in the equation of C^{MWRw} was statistically different from zero at a level of 0.3 % and is the only variable that is statistically different from zero in this equation. This seems to indicate that, in Colombia, the consumption of MWRw is mostly driven by the performance of the Colombian wood industry, and that the performance of the Colombian pulp and paper industry and the Colombian furniture industry do not have much effect, if any (see the coefficients of Eq. 10.1 in Table 4).

One likely reason for the limited significance of the furniture industry is the substantial shift in raw materials used in recent decades. The furniture industry, which once relied heavily on MWRw, has increasingly moved towards wood-based panels. Since these panels are classified under the wood industry in our model, this shift may contribute to the reduced impact of the furniture industry on MWRw consumption. For the pulp and paper industry, its consumption of MWRw constitutes only about 25 % of the total produced in Colombia. This relatively smaller proportion may also limit its apparent effect on the overall consumption of MWRw in the model. While these factors offer some explanation, other reasons could also contribute to the non-significant coefficients observed for these industries.

The coefficients for inflation (i) and wealth (W) variables included in the theoretical equations consistently produced incorrect signs in all estimation attempts. This anomaly likely arises from several factors: inflation might not impact wood consumption as theoretically expected due to price rigidity or market specifics in Colombia, while wealth may not directly boost wood product consumption if consumers allocate resources differently. Additionally, sector-specific dynamics, data aggregation issues, and endogeneity problems could have distorted the expected relationships. Consequently, to maintain the model's robustness and accuracy, these two variables were excluded from the final consumption shown in Tables 3 and 4.

As with the restrictions noted for the supply equations, our estimated consumption equations align with previous research regarding the signs and significance of explanatory variable coefficients. Kant et al. (1996) report similar negative effects of price and unemployment on w , f , and z consumption. This is consistent with findings from Simangunsong and Buongiorno (2001), Buongiorno and Zhu (2020), Schier et al. (2021), and Buongiorno (2021), which also demonstrate significant negative effects at levels below 5 % for most of the unprocessed and manufactured wood forest products.

5.1.2.2. Exports. The CFSM only includes estimated behavioral regression equations for exports (X) of w , f , z , and MWRw (X^w , X^f , X^z , and X^{MWRw} ; Eq. 11.1, 11.2, 11.3, and 11.4, respectively). The export equation for unprocessed wood for firewood (X^{FWrw}) could not be estimated due to negligible exports and unavailable full time series data. Initial OLS estimates for all four export equations exhibited autocorrelation and signs inconsistent with economic theory. These equations were re-estimated using CO and PW methods, resolving the issues for all except X^z (Eq. 11.3). For X^z , both the Global Industrial Production Index (IPI) and the ratio of the export price of z to the exchange rate (PX^z/RX) consistently showed coefficients not significantly different from zero, and PX^z/RX consistently had incorrect signs. Given the high coefficient of first-order autocorrelation (0.95) and the better fit for replicating historical data variability, the equation obtained by the PW method (Eq. 11.3 in Table 3) was retained for X^z .

In equations of X^w , X^f , and X^{MWRw} , the IPI coefficient was different from zero at the 2 % significance level. On the other hand, the coefficient of PX/RX was only statistically different from zero in the equation of exports of furniture (X^f), at the 1 % level. In the other three equations, it was different from zero only at higher (>15 %) significance levels. In equation of X^{MWRw} , the sign of the coefficient for PX/RX was wrong, though non-significant.

The relationships between X , IPI, PX/RX observed in this study are

generally consistent with previous research. Kant et al. (1996) reported similar signs and high significance for the impact of IPI on exports of w and f . For exports of paper (z), however, contrary to our findings, Kant et al. observed correct signs and high significance for the IPI coefficient. The results from Nanang (2010) and Karikallio et al. (2011) provide a basis for indirect comparison with our findings, revealing variations in significance and direction depending on the product and model used. Nanang (2010) observed mixed effects for different wood products, while Karikallio et al. (2011) reported varying impacts for paper, cardboard, and pulp exports. Details of the comparison with these two benchmarks are provided in Martínez-Cortés (2023). Coefficients with signs inconsistent with expectations and those not significantly different from zero, discussed in the previous paragraphs, may be attributed to Colombia's relatively low export levels and the abrupt changes in historical data from 1975 to 2015, particularly for w , z , and $MWrw$.

5.1.2.3. Imports. The CFSM does not include an import equation for unprocessed wood for firewood (M^{FWrw}) due to the lack of imports of this category of wood. For the equations of imports of manufactured wood products from w , f , and z industries (M^w , M^f , and M^z ; Eq. 12.1, 12.2, and 12.3 in Table 3, correspondingly), the explanatory variable of consumption (C) was different from zero at the 1.5 % significance level, the coefficient of the relative price of consumption with respect to import price (PC/PM) was statistically different from zero at equal or less than 10 % significance levels, and the coefficient of capacity utilization rate (CUR) of w , f , and z , respectively, was not different from zero (at 15 % or lower levels) in any of the three equations. In the M^f equation, we excluded the CUR due to its inconsistent sign. Regarding the import equation of $MWrw$ (M^{MWrw} , Eq. 12.4), the coefficient of the variable PC/PM was not statistically different from zero. In this equation, a fourth variable was included, the volume of $MWrw$ available for supply from forest plantations ($VAST^{MWfprw}$); the coefficient of this variable and that of the C^{MWrw} resulted different from zero at the 10 % significance level. The significant coefficient for $VAST^{MWfprw}$ indicates that this variable may be a useful indicator of potential shortages in the national supply of unprocessed wood for the manufactured wood products industry.

As in the case of exports, our findings for the import equations align with some previous studies, though with notable variations. Kant et al. (1996) found consistent signs and significance for the impact of consumption on imports of w , f , and z , similar to our results. However, there are differences in the relationship between imports and PC/PM , as well as the effects of CUR , which exhibit varying significance in our study. For example, in our study the coefficient of the former was only significant at the 10 % level and that of the latter was not only non-significant but with wrong sign (then dropped) in the M^f equation. Both studies found that CUR was not as significant as the other two variables in the equations for z . This general pattern is supported by broader literature, though with limited comparability, where the signs and significance of variables affecting imports of forest products vary, as noted in studies by Turner & Buongiorno (2004), Michinaka et al. (2011), Niquidet and Tang (2013), Sun (2014, 2017), Zhang et al. (2017), Sun and Zhou (2018), Muhammad and Jones (2021), Buongiorno (2018), Assogba and Zhang (2021), Adewuyi et al. (2021), and Buongiorno (2021).

Similarly, for the import equations, coefficients with signs inconsistent with expectations and those not significantly different from zero, as discussed earlier for the export equations, may be attributed to Colombia's relatively low trade levels and the abrupt changes in historical data from 1975 to 2015, particularly for $MWrw$. The incorrect sign of the CUR in the import equation for f , along with the low significance in the import equations for w and z , are more challenging to explain and warrant further research.

5.1.2.4. Consumption prices. The consumption price (PC) equations encountered several issues. In the initial estimations including absolute

terms for consumption prices (PC), the OLS estimates for PC^f and PC^z exhibited autocorrelation. Although the OLS estimates for PC^w , PC^{MWrw} , and PC^{FWrw} did not show autocorrelation, the coefficients had signs contrary to those predicted by economic theory. This issue with coefficient signs was also evident in the autocorrelated OLS estimates for PC^z . After re-estimating with CO and PW methods, only the PC^f was free from autocorrelation and retained the correct coefficient signs for all variable coefficients.

Similar issues were reported by Kant et al. (1996). Consistent with their approach and the strategy outlined earlier for addressing pricing issues in consumption equations, relative prices were used instead of absolute prices. This approach ensured that all five estimated consumption price equations were free of autocorrelation and displayed the correct signs in the OLS estimates as shown in Tables 3 and 4, Eq. 13.1, 13.2, 13.3, 13.4, and 13.5. For all these five estimated equations of prices of consumption coefficients of all variables were statistically different from zero. The coefficients of relative prices of consumption achieve this at levels of significance <0.01 %, even when using the robust standard errors (which correct for heteroscedasticity⁹). This could be interpreted as empirical evidence of the sticky nature of prices of consumption in the forest sector. Coefficients for Supply (National Production) of the respective group of wood forest products, the other variable included in all five consumption price equations are also different from zero at a level of significance <10 % (with robust standard errors).

5.1.2.5. Export prices. For all export price (PX) equations, the initial OLS estimates of coefficients were consistent with economic theory. However, equations for PX^w , PX^f and PX^z exhibited autocorrelation. After applying CO and PW methods, only the PW estimate for PX^w was both free from autocorrelation and had coefficients with signs consistent with economic theory. Consequently, the CFSM includes two OLS export price equations subject to autocorrelation (for PX^f and PX^z , Eq. 14.2 and 14.3), and two equations free from autocorrelation (including PX^{MWrw} (Eq. 14.4) estimated by OLS method and PX^w (Eq. 14.1) estimated by PW method). Eq. 14.4 excluded the World Export price Index (WEPI) due to its coefficient sign not aligning with economic theory. All coefficients of the accepted estimated equations for PX^w , PX^f , PX^z , and PX^{MWrw} have the correct signs, and all OLS estimated equations accepted are subject to heteroscedasticity of the residuals.

Most of the variables included in the accepted equations of the price of exports are statistically different from zero at usual levels of significance at least in some equations. Lagged price of exports (PX_{t-1}) was different from zero at significance levels <5 % in the equations of PX^w , PX^f , and PX^{MWrw} . Similarly, the exchange rate (RX) was different from zero at levels of significance <1 % only for the equations of PX^w , PX^z , and PX^{MWrw} . Finally, the coefficient of WEPI in the equations of PX^f and PX^z was statistically different from zero at levels of 5 %.

5.1.2.6. Import prices. The import price (PM) equations included in CFSM (PM^w , PM^f , PM^z , PM^{MWrw} , Eq. 15.1, 15.2, 15.3 and 15.4) are a mix of AR(1) CO, AR(1) PW, and OLS estimates. The OLS estimates for the equation of PM^{MWrw} have the correct signs and are all free of autocorrelation. Import prices for products of the manufactured wood products industry (i.e., PM^w , PM^f and PM^z) are highly dependent on their corresponding lagged prices (PM_{t-1}) and on the exchange rate (RX). For the three equations, estimated coefficients of these variables were different from zero at levels of significance <1 %. The other variable included in this equation, the relative price of the current consumption price to the

⁹ "...heteroscedasticity does not destroy the unbiasedness and consistency properties of the OLS estimators, but they are no longer efficient, not even asymptotically (i.e., large sample size). This lack of efficiency makes the usual hypothesis-testing procedure of dubious value." Gujarati and Dawn (2009, p. 415)

Table 4
Final Estimated Behavioral Equations for the UWM of the CFSM.

Equation number	Equation name	Method of estimation	Description	Estimated Equation												
8.4	Supply (Production) of unprocessed wood for the manufactured wood products industry & final consumption other than firewood from forest plantations	AR(1) PW - Prais-Winsten	Regression Equation t statistics	$S_t^{MWrw} = -3.2027099 + 16.2377453 VAST_t^{MWrw} + 415.7631690 PS_t^{MWrw}$	-3.2027099 -0.04	16.2377453 2.2	VAST ^{MWrw}	415.7631690 2.0	PS ^{MWrw}	Rho (AR1) = 0.90	12.41	SEE/MDV = 18.9%				
8.5	Supply (Production) of unprocessed wood for the manufactured wood products industry & final consumption other than firewood from natural forest	AR(1) CO - Cochrane-Orcutt	Regression Equation t statistics	$S_t^{MWrw} = -201.7925567 + 467.0081259 PS_t^{MWrw} + 0.0422465 NRT$	-201.7925567 -0.2	467.0081259 5.4	PS ^{MWrw}	0.0422465 0.4	NRT	Rho (AR1) = 0.74	6.779	SEE/MDV = 12.2%				
8.6	Supply (Production) of unprocessed wood for firewood from natural forest	AR(1) CO - Cochrane-Orcutt	Regression Equation t statistics	$S_t^{FWrw} = 1940.6284430 + 1.8886851 PS_t^{FWrw} / PS_t^{MWrw} + 11690.3709618 NRT/Nt$	1940.6284430 -2.6	1.8886851 0.013	PS ^{FWrw} / PS ^{MWrw}	11690.3709618 3.5	NRT/Nt	Rho (AR1) = 0.94	16.82	SEE/MDV = 9.1%				
10.1	Consumption of unprocessed wood for the manufactured wood products industry & final consumption other than firewood	AR(1) CO - Cochrane-Orcutt	Regression Equation t statistics	$C_t^{MWrw} / Y_t = 0.0007846 + 0.1032182 S_t^w / Y_t + 0.0223671 S_t^f / Y_t + 0.0196760 S_t^z / Y_t - 0.0191429 PC_t^{MWrw} / P_t^{nom}$	0.0007846 1.6	0.1032182 3.1	S ^w / Y _t	0.0223671 0.7	S ^f / Y _t	0.0196760 1.1	S ^z / Y _t	-0.0191429 -0.8	PC ^{MWrw} / P _t ^{nom}	Rho (AR1) = 0.85	9.697	SEE/MDV = 5.8%
10.2	Consumption of unprocessed wood for firewood	AR(1) CO - Cochrane-Orcutt	Regression Equation t statistics	$C_t^{FWrw} / Y_t = 0.0048151 - 0.0000283 U_t - 0.0045057 PC_t^{FWrw} + 0.0001756 NRT/NHHT$	0.0048151 2.2	-0.0000283 -1.0	U _t	-0.0045057 -3.4	PC ^{FWrw}	0.0001756 0.1	NRT/NHHT			Rho (AR1) = 0.92	14.6	SEE/MDV = 12.5%
11.4	Exports of unprocessed wood for the manufactured wood products industry & final consumption other than firewood	AR(1) CO - Cochrane-Orcutt	Regression Equation t statistics	$X_t^{MWrw} = -31.9361609 + 53.8771424 IPI_t + 20609.7204062 PX_t^{MWrw} / RX_t$	-31.9361609 -2.3	53.8771424 2.5	IPI _t	20609.7204062 0.9	PX ^{MWrw} / RX _t	Rho (AR1) = 0.55	4.064	SEE/MDV = 68.1%				
12.4	Imports of unprocessed wood for the manufactured wood products industry & final consumption other than firewood	AR(1) PW - Prais-Winsten	Regression Equation t statistics	$M_t^{MWrw} = 0.5643122 + 0.0069777 C_t^{MWrw} + 0.0405855 PC_t^{MWrw} / PM_t^{MWrw} - 0.3547749 VAST_t^{MWrw}$	0.5643122 0.3	0.0069777 1.3	C ^{MWrw}	0.0405855 0.1	PC ^{MWrw} / PM ^{MWrw}	-0.3547749 -1.3	VAST ^{MWrw}			Rho (AR1) = 0.46	3.116	SEE/MDV = 3.3%
13.4	Consumption price of unprocessed wood for the manufactured wood products industry & final consumption other than firewood	OLS - Ordinary least squares	Regression Equation t statistics t statistics with robust standard errors	$PC_t^{MWrw} / P_t^{nom} = 0.0042496 - 0.000000269 S_t^{MWrw} - 0.000002352 S_t^{MWrw} + 0.728509717 PC_{t-1}^{MWrw} / P_{t-1}^{nom}$	0.0042496 2.1	-0.000000269 -0.4	S ^{MWrw}	-0.000002352 -1.6	S ^{MWrw}	0.728509717 5.8	PC _{t-1} ^{MWrw} / P _{t-1} ^{nom}				SEE/MDV = 6.4%	
13.5	Consumption price of unprocessed wood for firewood	OLS - Ordinary least squares	Regression Equation t statistics with robust standard errors	$PC_t^{FWrw} / PC_t^{Cd} = 0.00080659 - 0.00000077 S_t^{FWrw} + 0.94778076 PC_{t-1}^{FWrw} / PC_{t-1}^{Cd}$	0.00080659 2.0	-0.00000077 -2.0	S ^{FWrw}	0.94778076 27.4	PC _{t-1} ^{FWrw} / PC _{t-1} ^{Cd}					SEE/MDV = 5.1%		
14.4	Export price of unprocessed wood for the manufactured wood products industry & final consumption other than firewood	OLS - Ordinary least squares	Regression Equation t statistics t statistics with robust standard errors	$PX_t^{MWrw} = -0.006795 + 0.889285 PX_{t-1}^{MWrw} + 0.0000050 RX_t$	-0.006795 -0.4	0.889285 9.6	PX _{t-1} ^{MWrw}	0.0000050 2.0	RX _t					SEE/MDV = 26.3%		
15.4	Import price of unprocessed wood for the manufactured wood products industry & final consumption other than firewood	OLS - Ordinary least squares	Regression Equation t statistics t statistics with robust standard errors	$PM_t^{MWrw} = -0.0127863 + 0.2062113 PM_{t-1}^{MWrw} + 0.0216517 PC_t^{MWrw} / PC_{t-1}^{MWrw} + 0.0001909 RX_t$	-0.0127863 0.0	0.2062113 1.2	PM _{t-1} ^{MWrw}	0.0216517 0.040	PC ^{MWrw} / PC _{t-1} ^{MWrw}	0.0001909 2.9	RX _t				SEE/MDV = 75.0%	

Source: Martínez-Cortés (2023).

one-period lagged consumption price (PC_t/PC_{t-1}) was not statistically different from zero at ≤15 % significance level) in any equation. For the import price equation of MWrw (PM^{MWrw}, Eq. 15.4), the exchange rate (RX) was the only variable statistically different from zero at 15 % significance (t statistics calculated with robust standard error due to the presence of heteroscedasticity).

The price equations for consumption, exports, and imports in our study show strong alignment with the findings of Kant et al. (1996). For consumption prices, both studies identified significant relationships between prices and national supply (S) for w, f, and z. Similarly, one-period lagged prices were consistently significant across these product groups in our study, reflecting the high significance levels reported by Kant et al. (1996). Regarding export prices, both studies found significant relationships with one-period lagged export prices and exchange rates, especially for w and z, although our results exhibited more consistent significance for global price indices. For import prices, both studies demonstrated significant relationships with one-period lagged import prices and exchange rates for w, f, and z. Unfortunately, the study of Kant et al. (1996) does not include the equations of prices for MWrw, leaving us without bases for benchmarking our PC^{MWrw}, PX^{MWrw}, and PM^{MWrw} estimated eqs.

A more detailed comparison of our results with other studies was carried out using the elasticities derived from the coefficients of the estimated equations presented in Tables 3 and 4. However, this information will be fully addressed in a comprehensive paper on the elasticities derived from CFSM estimations, which is currently being completed and will be published in due course. For now, please refer to Martínez-Cortés (2023) for further details on these comparisons.

5.2. The CFSM validation

The case of CFSM working as a unit (i.e., all its markets connected) seems to be the closest to real life, and therefore, we discuss the results of model validation for this case in detail. The results for the other two cases (i.e., individual equation in isolation and each market working independently from others) are briefly discussed as a comparator. Their details are available in Martínez-Cortés (2023). We, following Fair (1986) and Pindyck and Rubinfeld (1998), group the simulations into ex post simulations (1977–2015) and ex post forecasts (2016–2018). The latter include those executed to test stimuli responses and overall sensitivity of the model.

5.2.1. Ex post simulations

In the case of Non-MCC, the measures of performance of the CFSM are the same for both cases of validation, with and without the FWrw market (Appendix C1). Only for 9 (out of 32) equations, U₂ statistic signals that they perform equal or somewhat inferior than the naïve method of extrapolation. Nevertheless, other statistics such as R, mean of P, and the U_m and U_c indicate that the performance of those equations did not significantly worsen. In general, it can be said that, in the absence of market-clearing, with and without the FWrw market, the equations of the CFSM perform relatively well, their predicted series of the endogenous variables track very well the actual values, and no significant issue of systematic bias and replicability of the variation of the actual series is present.

For the MCC case, solutions were found only when the CFSM was executed without considering the FWrw market (Appendix C2). Also, these solutions covered only the period 1997–2015, as for the years 1977–1996 no viable solutions for the MCC of the aggregated market

were found, i.e., the WFP (without FWRw), which means that this market was far from clearing. In this case, the CFSM (without the FWRw market) predicts 33 endogenous variables, 29 using behavioral equations and 4 (the prices of supply PS) using the clearing identities.

The results indicate that the 29 behavioral equations of the CFSM, without including the FWRw market, perform well. The model is able to predict 26 out of 29 endogenous variables without major issues, i.e., close means of individual predictions P_t and actual values A_t , good linear relation with positive slope between P_t and A_t , no systematic bias, good replicability of the variation of A_t , and major share of the rmse coming from unsystematic error.

In the case of three other endogenous variables, the S^W equation performs inferiorly than the performance of the isolated equation ($U_2 = 1.31$, see Appendix C2), and the equation exhibits some systematic bias ($U^m = 0.19$). The explanation for this negative change can be attributed to the PS^W values forecasted by the solver to find the MCC in the market of w , which are lower than the actual values, that reduce the forecasted S^W and widen the rms prediction error of this endogenous variable.

For PM^{MWRw} and M^{MWRw} equations, issues on replicability of the variation of the actual data series for the first, and good tracking of A_t for both emerged. These problems were already present for the behavioral equations when validated in isolation. The main culprit for the lack of tracking of the P_t in relation to that of the A_t are the outliers of the actual data for PM and the intermittent data of M, which did not allow for an estimation of equations with good statistical properties for these two variables.

Finally, regarding the endogenous variables PS^w , PS^f , PS^z and PS^{MWRw} it is worth noting that values of forecast accuracy statistics are quite similar to those of markets in isolation (See Appendix C2).

5.2.2. Ex post forecast

Measures of forecast accuracy for equations in isolation and the complete CFSM (without FWRw) for the MCC of the period 1997–2018 were quite similar to those of 1997–2015. Also, measures of forecast accuracy for the Non-MCC case signaled that equations perform well. Hence, it can be concluded that the model equations in isolation give a good forecasting of the 29 endogenous variables they represent and that the CFSM (without FWRw), can consistently predict 29 and 33 endogenous key variables of the Colombian WFP market under the non-clearing and clearing cases of this aggregated market, respectively.

5.2.3. Responses to stimuli and overall sensitivity of the CFSM

Measures of forecast accuracy for the 1982–2018 simulation and the 1977–2018 simulation were not significantly different for individual equations interacting in the context of isolated markets. Also, for equations interacting in the context of the CFSM as a unit (i.e., as the WFP market, without FWRw) under the MCC case, the measures of forecast accuracy for the 2002–2018 simulation were not different from those of the 1997–2018 simulation. On the other side, the model responded to stimuli according to the elasticities obtained from the coefficients of the estimated model equations. Hence, the CFSM can be considered robust and reliable. However, no other relationship between VAST, K, and HCS and the rest of the variables of the CFSM have been estimated for comparison.

For further discussion on the CFSM estimation and validation results, please consult [Martínez-Cortés \(2023\)](#).

6. Applications of the CFSM

Using the CFSM, three empirical exercises have been conducted to produce crucial numerical input for the studies of Colombia's forest sector, including its forest policy.

First, utilizing the Colombian Forest Plantation Growth and Yield Simulator (SCRPFY), the availability of unprocessed wood from commercial forest plantations, VAS^{MWRw} (the key variable to compute the VAST, see Appendix B) was estimated for the period 2015–2047 under

several plantation expansion scenarios. The current policy of expanding Colombian plantations from 0.3 million hectares (Mha) in December 2015 to 1.5 Mha by 2025 was simulated. Additionally, alternative policy goals of reaching 0.45 Mha, 0.765 Mha, and 2.0 Mha under sustained rotation, as well as harvesting 0.3 Mha without replanting, were also considered. Simulation results indicated that the current policy expansion of plantations would increase the available industrial wood volume from plantations fivefold over the period 2015–2047, averaging 20.8 million m^3 of underbark roundwood annually. These impacts, in physical terms, on the unprocessed wood market consequently affect the manufactured wood forest product market, including the potential for forest industry expansion (please refer to [Martínez-Cortés et al. \(2022\)](#) for details).

Second, using the complete CFSM and the physical volumes of wood produced in the above exercise, the monetary impacts of five policy goals on the unprocessed wood market were estimated. Expanding Colombia's commercial forest plantations to 1.5 Mha by 2025 is projected to significantly affect the unprocessed wood market, with wood supply and exports expected to increase by 2.5 and 14.5 times, respectively, over the next 25 years. Concurrently, the supply price would decrease by 24 % compared to a scenario without plantation expansion.

Lastly, the complete CFSM and the input from both empirical exercises were used to examine the monetary impacts of a 5.5-fold increase in Colombia's manufactured wood forest products industry's production capacity from 2023 to 2038. This scenario projected an 8 % increase in the consumption of unprocessed wood and manufactured wood products of the pulp and paper industry over the next 25 years compared to a no-expansion scenario. Additionally, imports of manufactured products from the furniture industry would decrease by 35 %, and imports of pulp and paper products by 25 %, on average. These two latter empirical exercises are detailed in [Martínez-Cortés \(2023\)](#).

7. Conclusions

In this paper, we presented a framework for constructing national-scale forest sector models (FSMs) in tropical countries and demonstrated, through the case of the Colombian Forest Sector Model (CFSM), that the estimation of such models is feasible even in the presence of all possible challenges related to data availability, collection, and consolidation. Our framework is comprehensive, highly flexible, easy to follow, modular, and data-efficient. It covers the essential aspects of forest sector modeling, including both the representation of forest markets and the biological behavior of forest ecosystems, ensuring that all critical variables are incorporated for reliable sectoral analysis. The framework can adapt to various levels of data aggregation and accommodate one, two, or multiple markets, whether aggregated or individual, for any combination of the three product groups within the sector: wood and non-wood forest products, and forest ecosystem services, derived from any combination of four sources: forest plantations, natural forests, agroforestry systems, and trees outside forests.

The framework features a clear, logical structure with detailed guidelines for specification that facilitate its use by modellers and ensure that both the estimated forest sector model and its outputs are straightforward for stakeholders and policymakers to comprehend. Additionally, the framework supports phased development, allowing users to incrementally update and refine specific components without requiring a complete FSM overhaul. Moreover, the estimation of a forest sector model based on this framework relies on data from national accounts and other components of a country's National Statistical Systems, which are typically available in most tropical countries, along with recognized international data sources that are easily accessible online. This approach is cost-effective due to the regular collection and updating of these data sources, reducing the need for extensive data collection and streamlining the model's estimation process.

With the estimation and validation of the CFSM presented in this paper, we detail how to address data challenges for building FSMs in

tropical countries, as highlighted by Haynes (1993), and tackle the transparency issues associated with FSM complexity noted by Toppinen and Kuuluvainen (2010). The CFSM also addresses other challenges specific to tropical nations. Notably, it incorporates two unique features relevant to tropical contexts: the inclusion of unprocessed wood, specifically fuelwood, and the consideration of non-conventional wood sources, such as agroforestry and trees outside of forests. Furthermore, the current CFSM integrates a bio-physical forest growth simulator, which accounts for the physical volume of available wood in the unprocessed wood market model equations, thereby enhancing its practical value for policy analysis and other sectoral studies. The rigorous model validation process confirms that, despite the data challenges in tropical countries, highly reliable and useful forest sector models are achievable.

We believe that our primary contribution is addressing the longstanding absence of national-scale FSMs for tropical countries, an issue first highlighted by Haynes (1993). By estimating and validating the CFSM within our comprehensive framework, we effectively tackle this gap for the first time. The results of this paper will open a new chapter in Forest Sector Modeling in the tropical region, offering valuable insights for analyzing and addressing the existing and emerging issues related to the role of the forest sector in climate change, sustainable resource management, and biodiversity conservation.

Specifically for Colombia, the CFSM offers significant potential for analyzing a wide range of current and future forest policy issues, as well as supporting various other studies of the Colombian forest sector. In its current version, the CFSM can provide numerical inputs for analysis related to the development of the wood forest products market, the expansion of the manufactured wood products industry, the advancement of commercial forest plantations, and the management of natural forests. Its application in generating long-term numerical outputs for evaluating Colombia's 2018–2038 forest plantation value chain policy, as discussed in this paper, marks an important starting point. Although the current model does not include a dedicated simulator for natural forests, it can still conduct experiments to evaluate the effects of changes in wood harvest volumes from natural sources, offering insights that were previously inaccessible. Furthermore, the CFSM's forest plantation simulator is a valuable tool for analyzing current and future carbon markets, as it enables the estimation of actual and potential wood volumes by species and sites nationwide, forming the basis for CO₂ offset calculations. These calculations are also essential for Colombia's national studies and reports to the United Nations Framework Convention on Climate Change, which emphasize the role of forest plantations in addressing the climate crisis.

Once additional phases of the CFSM are developed, the model will offer a more comprehensive analytical view of the Colombian forest sector, particularly regarding policy pressures. In addition to providing detailed insights into wood forest products sourced from Colombia's natural forests, agroforestry systems, and trees outside forests, the CFSM will facilitate the analysis of agricultural policies related to agroforestry, such as land currently used for livestock and coffee. The model will also support studies on competing uses of forests, including forest ecosystem services and non-wood forest products. It will offer valuable inputs for understanding how forest restoration initiatives, biodiversity conservation efforts, and other ecological actions influence wood forest product markets and industries. Furthermore, it will enable more detailed and comprehensive analyses of the role of Colombian forests in addressing the global climate crisis.

The work presented in this paper not only advances the field of forest sector modeling but also provides critical guidance for policymakers and practitioners as follows. Firstly, given the critical role of tropical forests in the biggest challenge of this century – climate change, forest economists and modellers must overcome the preconception of the lack of suitable data for FSM in tropical countries. This preconception may be rooted in modellers' expectations of data availability from centralized data collection process of National Forest Services in temperate

countries. This paper demonstrates, the required data can be especially derived from a country's National Accounts and other national sources of information available for the forest sector, which have been significantly underexploited.

Secondly, the estimated CFSM model includes three markets for manufactured wood products and two markets for unprocessed wood. However, the proposed framework for FSM of tropical countries is highly flexible, and the new markets of wood products, such as bio-energy, non wood forest products, such as rubber, and forest ecosystem services, such as carbon, can be easily added with the availability of data for those markets. Similarly, unprocessed wood supply equations can be enhanced by including the estimation of these equations when separate data of unprocessed wood from agroforestry, trees from outside of forests, and recycled wood are available.

Thirdly, the proposed FSM (including the estimated CFSM) is a Structural Econometric Partial Equilibrium (SEPE model), and embedding of such SEPE model into a National General Equilibrium model is methodologically possible (Kant et al., 1996). Such an embedded model will open the doors to more complex analyses of the ecological, economic, and social impacts of the policies and decisions made in the forest sector on other sectors and vice-versa, which are so critical in the face of climate change. In addition, the use of a mix of micro and macroeconomic theoretical framework for capturing the dynamics of a forest sector (including the behavior of forest ecosystems), addresses the Lucas Critique (1976) with respect to the use of SEPE models, by capturing the resource limitations and other sectoral characteristics related to the available supply for unprocessed forest products.

Finally, our FSM framework and estimated CFSM were also subject to the inevitable simplifications and compromises inherent in every modeling endeavor.

This is particularly evident in adopting the competitive market theory for modeling the forest markets, despite the presence of market imperfections and policy distortions, especially in tropical countries. However, these distortions affect forest (and environmental) markets in both temperate and tropical regions, meaning that the limitations of our model are consistent with those in other forest sector models. The focus, therefore, should be on understanding and interpreting the results within the context of the existing market imperfections. Additionally, future changes in forest markets, such as shifts in the degree of monopoly or monopsony powers, the emergence of new uses of wood, and evolving dynamics in international trade regimes, should be continuously explored and incorporated to the extent possible.

In the CFSM estimation, some econometric compromises, such as a weak statistical fit and/or lack of statistically significant variable(s) in an equation, were also necessary. These are common compromises in sectoral models. The greatest strength of our estimated CFSM is that, despite these challenges and compromises, the model performed very well according to validation results, and the theoretical framework is highly flexible.

This paper has opened some new directions for research in FSMs. In Colombia, further research is essential, particularly for the informal firewood market, to improve the CFSM's accuracy and its integration with other markets of the forest sector. New markets for wood and non-wood products, i.e., bioenergy and rubber, and forest ecosystem services, i.e., carbon, and supply of wood from other sources, i.e., agroforestry, trees from outside forests, and recycled wood, should be included in the 2nd phase of the CFSM. Future enhancements could include spatializing the CFSM, integrating graphical interfaces with Colombian forest and climate monitoring systems, and linking the model to existing economic models to assess the forest sector's impact on Colombia's economy. Additionally, examining the impact of illegal logging and mining activities on market dynamics could provide deeper insights into the challenges and opportunities for refining forest sector modeling by including these factors. Similar studies are needed in other tropical countries.

CRedit authorship contribution statement

Oscar Geovani Martínez-Cortés: Writing – original draft, review & editing, Conceptualization, Methodology, Investigation, Data curation, Validation, Software, Formal analysis, Visualization. **Shashi Kant:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Henrieta Isuflari:** Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.forpol.2024.103341>.

References

- Abt, R.C., Cabbage, F.W., Pacheco, G., 2000. Southern forest resource assessment using the subregional timber supply (SRTS) model. *For. Prod. J.* 50 (4), 25–33.
- Adams, D.M., 1974. Forest product prices and national forest timber supply in the Douglas-fir region. *For. Sci.* 20, 243–259.
- Adams, D.M., Haynes, R.W., 1980. The 1980 softwood timber assessment market model: structure, projections, and policy simulations. *For. Sci. Monogr.* 26 (3), 1–22.
- Adams, D., Haynes, R., 1996. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 58 p (Ed.), *The 1993 timber assessment market model: Structure, projections, and policy simulations*. Gen. tech. rep. PNW-GTR-368. Portland, OR.
- Adams, D.M., Haynes, R.W., 2007a. The challenge of developing models to support forest sector policy analysis. In: Adams, D.M., Haynes, R.W. (Eds.), *Resource and Market Projections for Forest Policy Development: Twenty-Five Years of Experience with the US RPA Timber Assessment*. Springer Netherlands, Dordrecht, pp. 3–18. https://doi.org/10.1007/978-1-4020-6309-1_1. Retrieved from.
- Adams, D.M., Haynes, R.W., 2007b. The utility of forest sector models in addressing forest policy questions. In: Adams, D.M., Haynes, R.W. (Eds.), *Resource and Market Projections for Forest Policy Development: Twenty-Five Years of Experience with the US RPA Timber Assessment*. Springer Netherlands, Dordrecht, pp. 545–560. https://doi.org/10.1007/978-1-4020-6309-1_17. Retrieved from.
- Adewuyi, A., Ogebe, J.O., Oshota, S., 2021. The role of exchange rate and relative import price on sawnwood import demand in Africa: evidence from modified heterogeneous panel data methods. *J. Econ. Asymmetries* 24, e00231.
- Assogba, N.P., Zhang, D., 2021. US import demand for softwood plywood: a cointegration approach. *For. Sci.* 67 (2), 156–164.
- Bishop, J., 1997. Beyond price and volume: Forest sector models and the environment. In: *Models Needed to Assist in the Development of a National Fiber Supply Strategy for the 21st Century: Report of a Workshop*, 97(22), pp. 3–8.
- Borzykowski, N., 2019. A supply-demand modeling of the Swiss roundwood market: actors responsiveness and CO2 implications. *Forest Policy Econ.* 102, 100–113.
- Buongiorno, J., 1996. Forest sector modeling: a synthesis of econometrics, mathematical programming, and system dynamics methods. *Int. J. Forecast.* 12 (3), 329–343. [https://doi.org/10.1016/0169-2070\(96\)00668-1](https://doi.org/10.1016/0169-2070(96)00668-1).
- Buongiorno, J., 2014. Global modelling to predict timber production and prices: the GFPM approach. *Forestry* 88 (3), 291–303.
- Buongiorno, J., 2018. Projected effects of US tariffs on Canadian softwood lumber and newsprint imports: a cobweb model. *Can. J. For. Res.* 48 (11), 1351–1357.
- Buongiorno, J., 2021. GFPMX: a cobweb model of the global forest sector, with an application to the impact of the COVID-19 pandemic. *Sustainability* 13 (10), 5507.
- Buongiorno, J., Zhu, S., 2020. Calibrating and Updating the Global Forest Products Model GFPM Version 2017 (with BPMPD and Base Year 2017). Staff paper #90. Department of Forest and Wildlife Ecology, University of Wisconsin, Madison, 29p. Available at <http://labs.russell.wisc.edu/buongiorno/welcome/gfpm/>.
- Buongiorno, J., Zhu, S., Zhang, D., Turner, J., Tomberlin, D., 2003a. Chapter 4 – Model calibration and validation. In: Buongiorno, J., Zhu, S., Zhang, D., Turner, J., Tomberlin, D. (Eds.), *The Global Forest Products Model*. Academic Press, Burlington, pp. 57–88. <https://doi.org/10.1016/B978-012141362-0/50002-9>.
- Buongiorno, J., Zhu, S., Zhang, D., Turner, J., Tomberlin, D., 2003b. Chapter 1 - background and objectives. In: Buongiorno, J., Zhu, S., Zhang, D., Turner, J., Tomberlin, D. (Eds.), *The Global Forest Products Model*. Academic Press, Burlington, pp. 3–14. <https://doi.org/10.1016/B978-012141362-0/50002-9>.
- Buongiorno, J., Raunikar, R., Zhu, S., 2011. Consequences of increasing bioenergy demand on wood and forests: an application of the global forest products model. *J. For. Econ.* 17 (2), 214–229. <https://doi.org/10.1016/j.jfe.2011.02.008>.
- Cauria, S., Delacote, P., Lecocq, F., Barkaoui, A., 2009. Fuelwood Consumption, Restrictions about Resource Availability and Public policies: Impacts on the French Forest Sector. SSRN eLibrary.
- Cauria, S., Lecocq, F., Delacote, P., Barkaoui, A., 2010. In: INRA (Ed.), *The French Forest Sector Model: Version 1.0. Presentation and Theoretical Foundations*. INRA, Paris, France.
- Daigneault, A.J., Sohngen, B., Kim, S.J., 2016. Estimating welfare effects from supply shocks with dynamic factor demand models. *Forest Policy Econ.* 73, 41–51.
- DANE, 2013. Documento metodológico y resultados de la repopolación 1975–2005 Base 2005, 41 págs.
- DANE, 2020. Repopolación Base 2015. Nota metodológica. Junio de 2020. Bogotá DC, 43 pg.
- DANE, 2023. Cuenta Ambiental y Económica de Flujos del Bosque (CAE-FB). Balances oferta utilización e indicadores derivados. Base 2015. Actualizado el 30 de junio de 2023. Departamento Administrativo Nacional de Estadística de Colombia (DANE). Available at DANE - Cuenta satélite ambiental (CSA). Accessed on January 20, 2024.
- Dungan, P., Murphy, S., Wilson, T., 1995. National projections through 2015. *pol. study* 95-1. Institute for policy analysis, University of Toronto, pp. 1978–2011.
- Fair, R., 1986. Evaluating the predictive accuracy of models. *Handb. Econ.* 3, 1979–1995.
- FAO, 1994. In: Gaafar, E.F.A. (Ed.), *Studies on consumption of forest products in the Sudan - woodfuel consumption in the household sector - Forestry Development in the SUDANGPC/SUD/047/Net*. Khartoum.
- FAO, 2023. FAOSTAT Forestry Data Base. Food and Agriculture Organization of the United Nations, Rome. <http://faostat3.fao.org/download/F/FO/E>. Accessed on Dec 5, 2023.
- FAO, 2024. FAOSTAT Forestry Data Base. Accessed on June 6, 2024.
- Favero, A., Mendelsohn, R., Sohngen, B., 2018. Can the global forest sector survive 11°C warming? *Agric. Resour. Econ. Rev.* 47, 388–413.
- Favero, A., Mendelsohn, R., Sohngen, B., Stocker, B., 2021. Assessing the long-term interactions of climate change and timber markets on forest land and carbon storage. *Environ. Res. Lett.* 16 (1), 014051.
- Ferrer Velasco, R., Köthke, M., Lippe, M., Günter, S., 2020. Scale and context dependency of deforestation drivers: insights from spatial econometrics in the tropics. *PLoS One* 15 (1), e0226830.
- Folsland Bolkesjø, T., Trømborg, E., Solberg, B., 2006. Bioenergy from the forest sector: economic potential and interactions with timber and forest products markets in Norway. *Scand. J. For. Res.* 21 (2), 175–185. <https://doi.org/10.1080/02827580600591216>.
- Fox, J., 1984. Firewood consumption in a Nepali village. *Environmental Management* 8 (3), 243–250.
- Gane, M., 2007. The forest sector concept. In: *Forest Strategy*. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-5965-0_2.
- Gilles, J.K., Buongiorno, J., 1987. POPYRUS: a model of the North American pulp and paper industry. *For. Sci.* 33 (Monograph 28 (Supplement to Number 1, 1 March 1987)).
- Gujarati, D., Dawn, P., 2009. *Basic Econometrics*. McGraw-Hill Irwin, 2009. ISBN 0071276254, 9780071276252 5th Edition. 922 pages.
- Guo, J., Gong, P., Brännlund, R., 2019. Impacts of increasing bioenergy production on timber harvest and carbon emissions. *J. For. Econ.* 34 (3–4), 311–335.
- Haitovsky, Y., Treyz, G., Su, V., 1974. *Forecasts with Quarterly Macro Econometric Models*. National Bureau of Economic Research, New York.
- Hawkesworth, M.E., 1988. *Theoretical Issues in Policy Analysis*. State University of New York Press, Albany.
- Haynes, R.W., 1975. *A Dynamic, Spatial Equilibrium Model of the Softwood Timber Economy with Demand Equations Specified*. PhD Thesis. North Carolina State University, Raleigh.
- Haynes, R.W., 1993. *Forestry sector analysis for developing countries: Issues and methods*. Gen. tech. rep. PNW-GTR-314. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.
- ICA – Instituto Colombiano Agropecuario de Colombia, 2021. Reportes de la Base de Datos de Las Plantaciones Forestales Comerciales de Colombia June 30, 2021. Unpublished Excel files.
- Ince, P.J., Kramp, A.D., Skog, K.E., Spelter, H.N., Wear, D.N., 2011. U.S. forest products module: A technical document supporting the forest service 2010 RPA assessment (Research Paper FPL-RP-662 ed.). Forest Products Laboratory (U.S.). U.S. Dept. of

- Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. Retrieved from. <http://purl.fdlp.gov/GPO/gpo41527>.
- Jeuck, J.A., Cabbage, F.W., Abt, R.C., Bardon, R.E., McCarter, J.B., Coulston, J.W., Renkow, M.A., 2014. Assessing independent variables used in econometric modeling forest land use or land cover change: a meta-analysis. *Forests* 5 (7), 1532–1564.
- Johnston, Craig M.T., Van Kooten, G. Cornelis, 2014. Economic consequences of increased bioenergy demand. *For. Chron.* 90 (5), 636–642. <https://doi.org/10.5558/ftc2014-128>.
- Kallio, M., Dykstra, D.P., Binkley, C.S., 1987. *The Global Forest Sector. An Analytical Perspective*. John Wiley and Sons, Chichester, UK, 703 p.
- Kallio, A.M.I., Moiseyev, A., Solberg, B., 2004. The global forest sector model EFI-GTM: The model structure in: *EFI Technical Report: 15 European Forest Institute*. Retrieved from. <https://books.google.ca/books?id=g1eqNwAACAAJ>.
- Kallio, A.M.I., Moiseyev, A., Solberg, B., 2006. Economic impacts of increased forest conservation in Europe: a forest sector model analysis. *Environ. Sci. Pol.* 9 (5), 457–465. <https://doi.org/10.1016/j.envsci.2006.03.002>.
- Kant, S., Nautiyal, J.C., Ai-Ameen, W., 1996. The Canadian forest product sector: a sectoral econometric model. *Can. J. For. Res.* 26 (7), 1122–1134. <https://doi.org/10.1139/x26-125>.
- Karikallio, H., Mäki-Fräänti, P., Suhonen, N., 2011. Competition in the global pulp and paper industries—an evaluation based on three approaches. *J. For. Econ.* 17 (1), 91–104.
- Latta, G.S., Sjölie, H.K., Solberg, B., 2013. A review of recent developments and applications of partial equilibrium models of the forest sector. *J. For. Econ.* 19 (4), 350–360. <https://doi.org/10.1016/j.jfe.2013.06.006>.
- Lauri, P., Kallio, A.M.I., Schneider, U.A., 2012. Price of CO2 emissions and use of wood in Europe. *Forest Policy Econ.* 15, 123–131. <https://doi.org/10.1016/j.forpol.2011.10.003>.
- MADR, 2023. Estadísticas. Eslabón de la silvicultura y extracción de madera. Boletín Estadístico Forestal N° 7, 3–15. Marzo de 2023. Ministerio de Agricultura y Desarrollo Rural de Colombia (MADR). <https://observatorio-economia-foresta-1-3-Minambiente.hub.arcgis.com/pages/documentos>.
- MADS, 2023. Reporte de la base de datos Salvoconduco Único Nacional en Línea SUNL, años 2018 al 2021. Ministerio de Ambiente y Desarrollo Sostenible (MADS). Dirección de Bosques, Biodiversidad y Servicios Ecosistémicos (DBBSE). Archivo de Excel facilitado por la DBBSE, Bogotá DC, Colombia (14 de Agosto de 2023).
- Martínez-Cortés, Oscar Geovani, 2023. *The Colombian Forest Sector Model—An Analysis of Forest Plantation Policy in Colombia* (Doctoral dissertation, University of Toronto (Canada)), 257 p.
- Martínez-Cortés, Oscar Geovani, Kant, Shashi, 2024. Evolution of Colombia's market for manufactured products of the wood industry. *J.For.Bus.Res.* 3 (1), 34–59. <https://doi.org/10.62320/jfbr.v3i1.46>.
- Martínez-Cortés, Oscar Geovani, Kant, S., Isufllari, H., 2022. An analysis of wood availability under six policy scenarios of commercial forest plantations in Colombia. *Forest Policy Econ.* 138, 102722.
- McKillop, W., 1967. Supply and demand for forest products—an econometric study. *Hilgardia* 38 (1), 1–132. <https://doi.org/10.3733/hilg.v38n01p001>.
- Michinaka, T., Tachibana, S., Turner, J.A., 2011. Estimating price and income elasticities of demand for forest products: cluster analysis used as a tool in grouping. *Forest Policy Econ.* 13 (6), 435–445.
- Muhammad, A., Jones, K.G., 2021. The end of the trade war? Effects of tariff exclusions on US forest products in China. *Forest Policy Econ.* 122, 102350.
- Mustapha, Walid, 2016. *The Nordic Forest Sector Model (NFSM): Data and Model Structure*. Norwegian University of Life Sciences, Ås.
- Nakamura, E., Steinsson, J., 2013. Price rigidity: microeconomic evidence and macroeconomic implications. *Annu. Rev. Econ.* 5 (1), 133–163.
- Nanang, D.M., 2010. Analysis of export demand for Ghana's timber products: a multivariate co-integration approach. *J. For. Econ.* 16 (1), 47–61.
- Niquidet, K., Friesen, D., 2014. Bioenergy potential from wood residuals in Alberta: a positive mathematical programming approach. *Can. J. For. Res.* 44 (12), 1586–1594.
- Niquidet, K., Tang, J., 2013. Elasticity of demand for Canadian logs and lumber in China and Japan. *Can. J. For. Res.* 43 (12), 1196–1202.
- Olsson, O., Hillring, B., 2014. The wood fuel market in Denmark—Price development, market efficiency and internationalization. *Energy* 78, 141–148.
- Perez-Garcia, J., Joyce, L.A., Binkley, C.S., Mcguire, A.D., 1997. Economic impacts of climatic change on the global forest sector: an integrated ecological/economic assessment. *Crit. Rev. Environ. Sci. Technol.* 27 (sup1), 123–138. <https://doi.org/10.1080/10643389709388514>.
- Pindyck, R.S., Rubinfeld, D.L., 1998. *Econometric Models and Economic Forecasts*, 4th ed. Irwin/McGraw-Hill.
- Rivière, M., Cauria, S., 2021. Representations of the Forest Sector in Economic Models, pp. 521–553. <https://doi.org/10.4000/oeconomia.9418>. (*Economia - History/Methodology/Philosophy*, 2020, 10 (3). (hal-03088084).
- Robinson, V.L., 1974. An econometric model of softwood lumber and stumpage markets, 1947–1967. *For. Sci.* 20, 171–179.
- Ronnala, M., 1995. In: *International Institute of Applied Systems Analysis (Ed.), Medium-term scenarios for the Finnish pulp and paper industry*. Working Paper: 95-38.
- Schier, F., Morland, C., Dieter, M., Weimar, H., 2021. Estimating supply and demand elasticities of dissolving pulp, lignocellulose-based chemical derivatives and textile fibres in an emerging forest-based bioeconomy. *Forest Policy Econ.* 126, 102422.
- Schillinger, R.R., Adams, D.M., Latta, G.S., Van Nalts, A.K., 2003. An analysis of future private timber supply potential in western Oregon. *West. J. Appl. For.* 18 (3), 166.
- Schneider, U.A., Balkovic, J., De Cara, S., Franklin, O., Fritz, S., Havlik, P., Klaxner, F., 2008. The European forest and agriculture optimisation model—EUFASOM. In: *Working Paper no. FNU-156. Research Unit Sustainability and Global Change*. Hamburg University.
- Sedjo, R.A., Goetzl, A., 1997. Models needed to assist in the development of a national fiber supply strategy for the 21st century: Report of a workshop. Retrieved from. <http://www.rff.org/research/publications/models-needed-assist-development-national-fiber-supply-strategy-21st-century>.
- Sedjo, R.A., Lyon, K.S., 1996. Timber supply model 96: A global timber supply model with a pulpwood component. Retrieved from. <http://www.rff.org/research/publications/timber-supply-model-96-global-timber-supply-model-pulpwood-component>.
- Shahi, C., Kant, S., Yang, F.E., 2006. The law of one price in the North American softwood lumber markets. *For. Sci.* 52 (4), 353–366.
- Simangunsong, B.C., Buongiorno, J., 2001. International demand equations for forest products: a comparison of methods. *Scand. J. For. Res.* 16 (2), 155–172.
- Singh, B.K., Nautiyal, J.C., 1986. An econometric analysis of markets for Canadian lumber. *Wood Fiber Sci.* 18 (3), 382–396.
- Sjölie, H.K., Latta, G.S., Gobakken, T., Solberg, B., 2011. *NorFor—A Forest Sector Model of Norway: Model Overview and Structure*. INA fagrappport 18. Department of Ecology and Natural Resource Management Norwegian University of Life Sciences.
- Sjölie, H.K., Latta, G.S., Trømborg, E., Bolkesjø, T.F., Solberg, B., 2015. An assessment of forest sector modeling approaches: conceptual differences and quantitative comparison. *Scand. J. For. Res.* 30 (1), 60–72. <https://doi.org/10.1080/02827581.2014.999822>.
- Sohngen, B., Mendelsohn, R., 2003. An optimal control model of Forest carbon sequestration. *Am. J. Agric. Econ.* 85 (2), 448–457.
- Sohngen, B., Mendelsohn, R., Sedjo, R., 1999. Forest management, conservation, and global timber markets. *Am. J. Agric. Econ.* 81 (1999), 1–13.
- Solberg, B., 1986. Forest sector simulation models as methodological tools in forest policy analysis. *Silva Fennica* 20, 419–427.
- Sun, C., 2014. Recent growth in China's roundwood import and its global implications. *Forest Policy Econ.* 39, 43–53.
- Sun, C., 2017. Competition of wood products with different fiber transformation and import sources. *Forest Policy Econ.* 74, 30–39.
- Sun, C., Zhou, X., 2018. Imperfect competition in China's import market of roundwood and lumber products. *J. Agric. Appl. Econ.* 50 (2), 149–168.
- Theil, H., 1958. *Economic Forecasts and Policy*. North-Holland Pub, Amsterdam.
- Theil, H. 1966. *Applied economic forecasting*. H. Theil; assisted by G.A.C. Beerens, C.G. De Leeuw, C.B. Tilanus North-Holland Amsterdam.
- Toppinen, A., Kuuluvainen, J., 2010. Forest sector modelling in Europe—the state of the art and future research directions. *Forest Policy Econ.* 12 (1), 2–8. <https://doi.org/10.1016/j.forpol.2009.09.017>.
- Trømborg, E., Solberg, B., 1995. Beskrivelse av en partill likevektsmodell anvendt I prosjektet "Modellanalyse av norsk skogsektor [Description of a partial equilibrium model applied in the project "Modelling the Norwegian Forest Sector] Reserach paper of Skogforsk 14/95, 34 pp.
- Turner, J., Buongiorno, J., 2003. Issues and prospects in global forest sector modeling. In: Helles, F., Strange, N., Wichmann, L. (Eds.), *Recent Accomplishments in Applied Forest Economics Research (Forestry Sciences)*, 74. ed. Kluwer Academic Publishers, Dordrecht, Netherlands, pp. 193–205.
- Turner, J.A., Buongiorno, J., 2004. Estimating price and income elasticities of demand for imports of forest products from panel data. *Scandinavian journal of forest research* 19 (4), 358–373.
- Van Kooten, G.C., Johnston, C., 2014. Global impacts of Russian log export restrictions and the Canada–US lumber dispute: modeling trade in logs and lumber. *Forest Policy Econ.* 39, 54–66.
- Zhang, D., Buongiorno, J., Zhu, S., 1997. Forestry and Planning division. In: *Food and Agricultural Organization of the United Nations (Ed.), Trends and Outlook for Forest Products Consumption, Production and Trade in the Asia-Pacific Region*. (Working Paper APFSOS/WP/12. ed.). Rome.
- Zhang, H., Kuuluvainen, J., Lin, Y., Gao, P., Yang, H., 2017. Cointegration in China's log import demand: price endogeneity and structural change. *J. For. Econ.* 27, 99–109.