Forest Sector Models for Tropical Countries - A Case Study of Colombia

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1. Introduction

The development of Forest Sector Models (FSMs) represents a significant milestone in the fields of forest economics and policy analysis. Rivière & 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.

Following McKillop's initial efforts, several other FSMs emerged in the United States (U.S.) before the mid-1970s. Notable among these were Adams D.M.'s 1974 timber market model in Douglas fir regions, Robinson V.L.'s 1974 econometric model of softwood lumber and stumpage markets, and Haynes R.W's 1975 dynamic spatial equilibrium model for softwood timber. 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 & Haynes (1980, 1996) and the PAPYRUS/North American pulp and paper model (NAPAP) by Gilless & Buongiorno (1987). Concurrently, the scope of FSM development extended beyond the U.S.; a prime example is the Global Trade Model (GTM) (Kallio et al. 1987). By the late 1990s, many other global models, including the Global Forest Products Model (GFPM) by Zhang et al. (1997) and the Timber Supply Model (TSM) by Sedjo & Lyon (1996), emerged. TAMM, PAPYRUS, GTM and TSM models were instrumental in shaping the theoretical approach and methodologies that later became fundamental to FSM development (Latta et al. 2013). The evolution of FSMs since the 1960s is comprehensively documented in the works of Solberg (1986), Haynes (1993), Buongiorno (1996), Adams & Haynes (2007a, 2007b), Latta et al. (2013), Sjølie et al. (2015), and Rivière & 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 & 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. Adams & 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 & Kuuluvainen (2010), Latta et al. (2013), Guo & Brännlund (2019), and Favero et al. (2021).

Both the evolution of FSMs and their usage in forest policy analysis, have been reported at national, regional, and global scales (Toppinen & 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.

In addressing the data challenges highlighted by Haynes, the use of National Accounts as a framework and data source for developing national-level FSMs, as demonstrated by Kant et al. (1996), presents a promising solution but remains underexplored. In this paper, we build upon the approach of Kant et al. (1996) to propose a comprehensive framework that encompasses theoretical, conceptual, methodological, and empirical aspects of building national-scale FSMs tailored for tropical countries having established national accounting systems that align with the United Nations System of National Accounts standards. Using Colombia as a case study, we demonstrate the practical application of our framework by building the Colombian Forest Sector Model (CFSM). The CFSM addresses five key

[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).

considerations for building national-scale FSMs for tropical countries, which have not attracted much attention in FSMs. .

First, building FSMs requires forest sector and socioeconomic data in addition to data from national accounts system. In tropical countries, forest sector data is often collected by various government and non-government agencies, making its collection, compilation, and consolidation a challenge. We develop and conduct a comprehensive data consolidation process that includes meticulous collection, organization, and transformation of both historical and current data.

Second, FSMs have generally focused on manufactured wood products, while unprocessed (raw) wood markets have received less attention due to their insignificant share in developed economies. However, in tropical countries, unprocessed wood for firewood and for the manufactured wood products industry and final consumption other than firewood make significant contributions and should be considered separately in their FSMs. For example, in 2022, 74% of the 1.97 billion cubic meters of global production wood fuel was produced in tropical countries (FAO, 2024). In our model, we include two markets of raw wood: the market of unprocessed wood for firewood and for the manufactured wood products industry and final consumption other than firewood.

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. The area of agroforestry systems in Colombia (including 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). Trees outside forests (planted and naturally regenerated) have become relevant in Colombia and growing (ICA, 2021). Hence, wood supply from these two sources should be included in FSMs, and we include all four sources of wood supply in our model.

Fourth, most existing FSMs for temperate countries are economic models not linked to biophysical models of forests. These linkages are essential, particularly for policy analysis related to wood supply from different sources, such as commercial plantations. We developed a forest growth model and linked it to our economic FSM, incorporating physical wood supply as one of the explanatory variables in wood supply equations.

Fifth, rigorous model validation is essential to ensure the accuracy and reliability of FSMs. We developed a comprehensive Validation App in Excel® and used it to perform an extensive validation of the FSM. The App also retains all the original time series used for model estimation and executes (solves) the CFSM. By addressing both the first and fifth challenges in this manner, we mitigate the transparency issues that often arise due to the complexity of FSMs, as noted by Toppinen & Kuuluvainen (2010).

Next, we present our comprehensive framework for building FSMs for tropical countries. Methods of data collection, model estimation, and model validation are presented in Section 3, and results are given in Section 4. Model applications are discussed in Section 5. Finally, Section 6 concludes the paper with the main conclusions, limitations, and future research directions.

2. Theoretical Structure of The Forest Sector Model – The Case Study of Colombia

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; Buongiorno (2014, p. 291) discussed activities related to the growing, harvesting, transportation, and transformation of wood into wood products, and the use of wood products. Rivière & Caurla (2021) concluded 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, the comprehensive approach of Gane (2007, p. 32), which encompasses resources, activities, and output, all of which are intertwined in both space and time, seems to be more appropriate. In the forest sector, the resources encompass natural, human, and capital, and the natural resources comprise 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, biodiversity conservation, water protection, and nature tourism, to name a few.

We conceptualize the forest sector as the aggregate of all markets of WFP, NWFP, and FES. To represent a country's forest sector, we use a structural econometric partial equilibrium model based on the framework of neoclassical competitive market theory. This 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 outline for a complete model of the forest sector of Colombia, which includes WFP, NWFP, and FES, is presented in Appendix A.

For the sake of brevity, the CFSM conceptualized, estimated, and presented in this paper only includes WFP and corresponds to Phase I of the complete CFSM shown in Appendix A, as illustrated in Figure 1. The model comprises two market models: the manufactured wood products market sub-model (MWM) and the unprocessed wood market sub-model (UWM), as well as the Colombian Forest Plantation Growth and Yield Simulator (SCRPFC). The structures of the MWM and UWM are explained in the following subsections. The SCRPFC utilizes a biological model to project the volume availability of unprocessed wood from Colombia's forest plantations. This projection serves as an input for the volumes available for the supply of unprocessed wood (a variable in the behavioral equations of the UWM named VAST), which is either consumed as a final product or used as an input in the manufactured wood product industry. The simulator is detailed in Martínez-Cortés et al. (2022).

Please insert Figure 1 here

The UWM mimics 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 individual 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 B and summarized in Table 1. The name of the variables used, their abbreviations, and data sources are given in Table 2.

Please insert Table 1 and 2 here

In the MWM and UWM (see Figure 1) each of the two markets of the WFP market (i.e., rw and MW) is represented by a partial equilibrium sub-model (PEM). 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.

2.1. Identities of the Manufactured Wood Products Market sub-model (MWM) and the Unprocessed Wood Market sub-model (UWM)

For both MW and rw markets, supply is a composite of the individual supplies of each submarket within them ($ST_t^j = \Sigma_k S_t^{kj}$). As such, ST for the MW is the sum of the supplies of 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 the above four sources.

However, due to an increasing interest in forest plantation development by Colombia´s government (Martínez-Cortés et al., 2022), the CFSM provides a more detailed specification of wood supply from commercial forest plantations. Wood supply from natural forests is included in the CFSM either as a basic equation which depends only on the price of supply, or as a lump-sum estimation based on trends in the historical supply of wood from this source, as per the national wood consumption balances. Wood supply from agroforestry systems is modelled as part of supply from commercial forest plantations, and supply from trees outside forest is modelled as part of supply from 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 UWM sub-model, with a special focus on how the VAST variable is calculated, is provided in Appendix C.

The same identity equation holds for demand ($DT_t^j = \Sigma_k D_t^{kj}$). The identities that capture these relationships are presented in Table 1. For the sake of parsimony, the identity equations in this section are written in their general form, and the same apply to both sub-models of the CFSM: MWM and UWM. A more detailed description of the components of Supply and Demand in these two sub-models is presented below. The details of independent and dependent variables of each equation, and estimated regression coefficients are given in tables 3 & 4.

2.2. Supply-Specific Behavioral Equations

The supply (S_t^k) equations of the three individual markets under MWM include the following four explanatory variables of choice for the industry-specific (k): labor (L_t^k), capital (K_t^k), and prices (PS_t^k) of the manufactured wood products for the w, f, and z industries, and the price of the unprocessed wood for the manufactured wood products industry and final consumption other than firewood (PC_t^{MWrw}) (Eq. 8).

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 unprocessed wood, 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.

In the case of supply equations of individual markets within UWM, they include market (k)-specific labor (L_t^k), capital (K_t^k), as well as two additional variables: $VAST_t^k$ and GEN_t^k. The first variable VAST is the stock of wood available for supply at the beginning of year t, while GEN captures other costs of harvesting and those not captured by the L^k and K^k variables. Both are explained in detail in Appendix C.

2.3. Demand-Specific Behavioral Equations

Consumption (C)

In the case of the MWM, in addition to the usual variables of price of consumption (PC) and income (Y), three other macroeconomic variables, namely: unemployment (U), inflation (i) and wealth (W) are used as explanatory variables . 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). The consumption for products manufactured by the wood industry in 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 (Eq. 9).

For the UWM, consumption of unprocessed wood for the manufactured wood products industry and final consumption other than firewood (C_t^{MWrw}) is derived from the supply (production) of manufactured wood products of the wood (S^w), furniture (S^f), and pulp and paper (S^z) industries, and the price of its consumption (PC_t^{MWrw}). For the individual market of 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 consumption (C_t^{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 number of people per household (in this research rural population NR_t 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 this equation for consistency with the explanatory variables used to explain consumption in the MWM.

In the near future, current efforts from different Colombian government sources 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 C_t^{FWrw} (Eq. 10).

Exports (X)

In both (sub)models of the CSFM (i.e. MWM and UWM), the main determinants of exports of wood forest 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, which include US, receiving Colombian exports has changed and could continue to change in the future. As such, instead of country-specific indexes, better explanatory variables of wood products exports are the respective prices of exports (PX) for each group of unprocessed wood and manufactured wood products of the individual markets considered, as well as the World's Industrial Production Index (IPI) and Colombia's USD exchange rate (RX) (Eq 11).

Imports (M)

Colombia has a large 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 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 in demand stemming from a growing population and higher income levels.

Import equations for each group of wood products considered in both MWM and UWM include the usual explanatory variables that determine it: the consumption expenditure, together with the relative price of consumption with respect to imports, and the capacity utilization rate for each industry. For the UWM, we also include the volume available for supply (VAST) as an explanatory variable, as a possible indicator of shortages of national unprocessed wood for the manufactured wood products industry[2] (Eq 12).

2.4. Prices of C, X, and M

The prices for C, X, and M in both UWM and MWM are calculated based on the assumption that domestic goods and foreign goods are not perfect substitutes, and as such, different markets of the same manufactured wood products will be characterized by different prices. Therefore, the CFSM does not calculate one prevailing price for all demand components (consumption, exports, and imports) but it presents a separate price equation for each component, introducing thus three price equations for each of the unprocessed wood and manufactured wood products markets considered. This approach is based on literature that shows the realistic nature of cross border prices, which do not necessarily behave according to the Law of One Price economic principle due to trade frictions (tariffs), differences in quality between domestic and foreign products, and lack of perfect product substitution among aggregated items (; Shahi et al., 2006; Olsson & Hillring, 2014).

In addition to the above assumption, the equations for calculating the demand 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 & Steinsson, 2013). 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).

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

Therefore, the main determinants of the current price of consumption (PC) for each period t, are the total available supply for each market of unprocessed wood and manufactured wood products, and as explained above, the closing price of the preceding time period (Eq. 13).

As with exports, a better choice for determining the price of exports (XP) should include as explanatory variables the World Export Price Index (WEPI) for each of the products considered and Colombia's USD exchange rate, as well as the lagged price of exports (PX_{t-1}) for each of the unprocessed wood and manufactured wood products exported (Eq. 14).

Similar to the variables used by Kant et al. (1996), the price of imports (MP) for each group of unprocessed wood and manufactured wood products depends mainly on the USD exchange rate for Colombia, the previous period's import price, as well as the competing domestic consumption price for the same product (PC), derived in equation 13. Equation 15 in table 3 presents this relationship and concludes the theoretical structure of the CFSM.

3. Methods

3.1. Data collection and consolidation

A comprehensive data collection and consolidation process was used to address the complexities often faced in tropical countries where forest sector data is not centrally organized. This crucial step involved meticulous collection, organization, and transformation of both historical and current data, underpinning the estimations and assumptions within the CFSM. This extensive effort led to the development of Raw Data Tables, Transformation Tables, and Consolidated Data Tables for each equation of the CFSM, all intricately linked to their original sources. This linkage ensures a transparent and systematic progression from raw data to the final model inputs. The rigorous documentation method employed in constructing the CFSM effectively addresses the transparency issues often associated with the complexity of FSMs, a challenge highlighted by Toppinen & Kuuluvainen (2010).

Forest sector data scarcity issues in tropical countries, as highlighted by Haynes (1993), were addressed by utilizing extensive data from the Supply and Use Tables (SUT) of Colombia's National Accounts, covering the period from 1970 to 2020. This dataset was pivotal for the CFSM's dependent variables, encompassing supply quantities, as well as the quantities and prices of consumption, exports, and imports. To address the lack of detailed price information typical in tropical regions, we applied the Kant et al. (1996) methodology to generate price deflators for these variables within the same timeframe. These deflators were derived by comparing current and constant monetary quantity values of each forest sector aggregates from the SUT, providing a reliable measure of real price changes over time. For obtaining the data for the forest sector and macroeconomic independent variables of the theoretical equations, a variety of sources were utilized. These included digital data and paper-format publications from Colombia's National Statistics System, other private sources (e.g., DANE's Manufacturing Annual Survey, Colombia's Central Bank data repositories, Fedesarrollo's Enterprise/Industrial Opinion Survey) and international databases like FAO, World Bank, and FRED, as well as 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 supply, consumption, exports, and imports for MWrw and FWrw markets from 1970 to 1993, as well as 1970-2018 estimations for supply quantities at purchaser prices, Colombia's wealth, and asset values 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 C), legal and illegal, from all national sources of wood.

Despite these efforts, obtaining complete data for all variables was not always possible. Where data was missing, proxy variables were utilized as substitutes. Consequently, some variables, such as labor and capital for the logging industry of commercial forest plantations, as well as others capturing various costs and geographical locations, 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 firewood 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 firewood market from the CFSM's import and export equations, as well as from their corresponding price equations.

Finally, no equation for the supply of FWrw from forest plantations was estimated because in Colombia, firewood is supplied almost entirely from natural forests, with a minor supply from agroforestry systems and trees outside forests. Due to data constraints, it was not possible to estimate separate equations for these latter two ecosystems. Therefore, the supply, consumption, and trade of wood from agroforestry systems and trees outside forests are considered part of forest plantations and/or natural forests (see Appendix C for additional details).

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. This phase included standardizing units, adjusting base years, scaling, and normalizing variables to ensure time series stationarity. 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, 2020a). 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). 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 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 provides a detailed list of data sources for all variables used in the CFSM, along with their superscripts, time series used to be represented, and their units.

3.2. Parameter estimation of behavioral equations of the CFSM

Ordinary Least Square (OLS) was used for the parameter estimation of the final 32 behavioral equations included in the CFSM, 21 for the MWM and 11 equations for UWM. The estimations were conducted using IBM SPSS Statistics® 26.

The parameter estimation and selection of the final estimated equations process closely followed that in 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 non-computable, Graph methods (partial auto-correlogram), the Run test, and the Breusch–Godfrey were used[3]. If subject to first-order autocorrelation, it was addressed by using Prais-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-R^2 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 FSMs, the finally selected estimated equations are the result of "considerable specification searching, and classical interpretations of econometrics may not fully apply" (Kant at al., 1996, p. 1123) The details of the process of estimation and the final inclusion of each equation are available in Martínez-Cortés (2023).

3.3. 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 U_1 (Theil 1958) and U_2 (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

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

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".[4] 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 Simplex[5] and the Generalized Reduced Gradient (GRG Non-linear)[6] methods which are already part of the add-on modules in Microsoft Excel Solver®.

As the raw material for the products included in the 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 modelled, the validation for the CFSM was also done without considering the FWrw market (i.e., "turning off" the partial equilibrium model for FWrw).

Finally, as per Pindyck & Rubinfield (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.

4. Results

4.1. Final estimated behavioral equations of the CFSM

The results of the estimation of all equations finally included in the MWM and UWM of the CFSM are presented in tables 3 and 4, respectively. For a better interpretation, in addition to the final estimated behavioral (regression) equations, these tables include the values of the t statistic, t statistic with robust

[4] The reader can see the connecting variable among PEMs as follows: PC^{MWrw} as a normalized independent variable in the Supply Equations 16, 17, and 18 (table 3); S^w, S^f, S^z as independent variables in the Consumption Equation of MWrw (Eq 40) and PS^{MWrw} as normalizing variable in the Supply Equation of FWrw (Eq 39).

[5] Based on the Simplex Method "originally developed by Dantzig in 1948" (https://www.solver.com/linear-quadratic-programming accessed on August 19, 2022)

[6] 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)

standard errors (for OLS estimation), adjusted R^2, 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).

Please insert tables 3 and 4 here

Supply-side equations

All estimated coefficients have the correct signs, i.e., in agreement with economic theory, and most coefficients were significantly different from zero. The coefficient of the VAST (a key policy variable of the CFSM) for S^{MWfprw} (Eq 37) was statistically significant and different from zero but at a 15% level of significance. The coefficient of the price of supply (PS) in all equations was also different from zero at levels of significance of 5% in the mentioned equation and in that of S^w (Eq 16), and at 1% in equations of S^f, S^z and S^{MWnfrw}. In the supply equations for the f and z industries, the coefficients of capital and labor 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 in the equation of supply of unprocessed wood for firewood (S^{FWnfrw}, Eq 39) 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^{MWnfrw}, and the relative supply price of unprocessed wood for firewood (PS^{FWnfrw}/PS^{MWrw}) in the equation of S^{FWnfrw}. The variable of capital of the w industry (K^w) was excluded from Eq 16 because in all tries of estimation its sign was not in agreement with the economic theory.

Demand-side equations

Consumption

In all estimated equations, signs of the coefficients agree with those expected by economic theory, but their significance levels have a wide variation. Prices of consumption in equation of C^z (Eq 21) and C^{FWrw} (Eq 41) 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 20, 19 and 40, 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 40 in Table 4). As the coefficients of inflation (i) and wealth (W) variables, which were included in the theoretical equations to be estimated, resulted with wrong signs in all estimation attempts, these two variables were dropped from the final consumption equations accepted for the CFSM.

Exports

The CFSM only includes estimated behavioral regression equations for exports of w, f, z, and MWrw (Eq 22, 23, 24, and 42, respectively). It was not possible to estimate the export equation for unprocessed wood for firewood (X^{FWrw}), as exports of this were negligible for many years and full time series data was not available. 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.

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 (Eq 25, 26, and 27, correspondingly), the explanatory variable of consumption (C^{j}) was different from zero at the 1.5% significance level, the coefficient of the relative price of consumption with respect to import price (PC^{j}/PM^{j}) was statistically different from zero at equal or less than 10% significance levels, and the coefficient of capacity utilization rate (CUR) was not different from zero (at 15% or lower levels) in any of the three equations.

Regarding the import equation of unprocessed wood for the manufactured wood products industry and final consumption other than firewood - M^{MWrw} (Eq 43), the coefficient of the variable PC/PM was not statistically different from zero. In this equation, a fourth variable was included, the $VAST^{MWfprw}$; the coefficient of this variable and that of the C^{MWrw} resulted different from zero at the 10% significance level.

Consumption prices

In all five estimated equations of prices of consumption (Eq 28, 29, 30, 44, and 45) 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 heteroscedasticity[7]). 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).

Export prices

All coefficients of the accepted estimated equations for of PX^w, PX^f, PX^z, and PX^{MWrw} (Eq 31, 32, 33, and 46, respectively) have the correct signs and all OLS estimated equations accepted are subject to heteroscedasticity of the residuals. The explanatory variable World Export price Index of w ($WEPI^w$) included in the theoretical equation for the PX^{MWrw} (see Eq 14 in table 1) was dropped in the Eq 46 as the estimated coefficient sign was not in agreement with economic theory.

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%.

Import prices

Import prices for products of the manufactured wood products industry (i.e., PM^w, PM^f and PM^z, Eq. 34, 35, and 36, correspondingly) 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 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 47), 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).

[7] "…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)

4.2. Results of Model Validation

The case of CFSM working as a unit (i.e., all 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 and details are available in Martínez-Cortés (2023). We, following Fair (1986) and Pindick & Rubinfield (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.

4.2.1 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 D1). Only for 9 (out of 32) equations, U_2 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 D2). 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 sub-model, 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 D2), 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 D2).

4.2.2 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.

4.2.3 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.

5. Model's Applications

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 (SCRPFC), the availability of unprocessed wood from commercial forest plantations, VAS^{MWfprw} (the key variable to compute the VAST, see Appendix C) 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 the 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).

6. Conclusions

In this paper, we presented a framework for constructing country-specific forest sector models in tropical countries and demonstrated that the estimation of such models is possible in tropical countries even in the presence of all possible challenges related to data availability, collection, and consolidation. In addition to data challenges, two specific features related to tropical countries – importance and the need of the inclusion of unprocessed wood, specifically fuelwood, and the inclusion of non-conventional sources of wood supply – agroforestry and trees outside of forests – are the unique features of the CFSM. Similarly, inclusion of the physical volume of available wood as an explanatory variable of economy wood supply by linking bio-physical forest growth simulator to the CFSM enhances the applied value of the model, and the rigorous model validation process confirms that even with many data challenges in tropical countries, highly reliable and useful forest sector models are possible. We believe that the CFSM and the results of this paper will open a new chapter of Forest Sector Modeling in Tropical countries and their applications to analyze and address the existing and emerging issues related to the role of forest sector in climate change, sustainable resource management, and biodiversity conservation. The paper makes at least three higher level – beyond its model and analysis – contributions.

First, given the critical role of tropical forests in the biggest challenge of this century – climate change, forest economists and modellers have to 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. The use of data from the National Accounts and other components of National Statistical Systems will be cost-effective due to its regular collection and updating.

Second, the estimated CFSM model includes three markets for manufactured wood products and two markets for unprocessed wood products . However, the proposed framework for FSM of tropical countries is highly flexible, and the new markets of wood products, such as bioenergy, 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.

Third, 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, this is the first FSM of a tropical country based on National Accounts data, and simplifications and compromises are inevitable in every modeling project.

This is particularly evident in adopting the competitive market theory, despite market imperfections and policy distortions, for modelling the forest markets, specifically in tropical countries. However, forest and environmental markets are subject to these distortions in temperate as well as tropical countries, and therefore the limitations of our model are similar to other forest sector models, and the emphasis should be on understanding and interpreting the results in the context of the existing market imperfections. Similarly, future changes in forest markets, such as changes in the degree of monopoly or monopsony powers, new uses of wood, and dynamics of international trade regimes, should be continuously explored and incorporated to the possible extent.

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

The 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 model's accuracy and 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 CFSM. Future enhancements may 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, the impact of illegal logging and mining activities on market dynamics can provide deeper insights into the sector's challenges and opportunities. Similar studies are needed in other tropical countries.

Declaration of Competing Interest

Authors declare no competing interests.

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