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A meta-analysis on wood trade flow modeling concepts

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ABSTRACT

Papers on forests and forest products often address sustainability and climate change issues. Wood trade flow models study production and exchanges of wood products in order to better understand and analyze these issues. To date, there has not been a complete overview of these models' objectives, or of the wood trade flow factors they use. We expect wood trade flow models with different objectives to rely on a wide diversity of factors. We performed a meta-analysis on 499 publications about wood trade flow modeling, published between 1972 and 2022 and recorded in the Scopus database. We found that three groups of model objectives constitute most of the literature: understanding trade mechanisms (5% of the literature), forecasting trends (9%), and policy analysis (99%). There is a degree of overlap between these categories, as 14% of the literature uses wood trade flow models for at least two of the latter objectives. Within the category of models exploring or simulating policies, about 37% of papers address major economic disruption issues, 40% concern environmental issues, while 49% relate to energy, welfare or trade policies. Altogether, these models use a narrow set of four categories of factors: price factors (6% of the literature), the interdependency of production factors (11%), policy factors (15%), and stock and trade quantity factors (49%), neglecting other possible factors. This study provides the first comprehensive overview and categorization of the models' objectives in relation to their factors. Most importantly, the literature rarely uses certain factors that are considered in other commodities or economic sectors. In particular, the central role of urban dynamics in shaping material trade flows remains unexplored overall by wood trade flow modeling. Compared to the perception of what the driving forces of the forest sector economics have been in recent decades, new issues that have risen require the integration of new categories of factors.

1. Introduction

Sustainability and climate change are recurring themes in papers on issues surrounding forests and their products. Under certain conditions, forests and their products can contribute substantially to climate change mitigation, as forests sequester carbon from the atmosphere in forest biomass and soil through biological growth and provide wood-based products that store carbon (Canadell and Raupach, 2008). Such wood-based products can replace greenhouse gas-intensive materials or fossil fuels (Geng et al., 2017; Leskinen et al., 2018). The usage of forest biomass for bioenergy or as an ecological substitute for concrete and other mineral materials, or for plastic, has become critical for energy transition policies and for the use of sustainable materials in construction (IRENA, 2020; IPCC, 2022). Furthermore, wood products are commercial goods, and the trade of wood products is a complex web of global exchanges and local supply and demand. Wood products are subject to international trade conflicts with local and global repercussions. Trade restrictions between China and the United States (Pan et al., 2021), Russian roundwood export restrictions (Turner et al., 2008; Solberg et al., 2010), and the Canada-U.S. softwood lumber dispute (Johnston and van Kooten, 2017) all belong to this category. Forests and wood products are also subject to local changes of policies and regulations (Zhang and Li, 2009; Caurla et al., 2013), and domestic forces may be stronger than international demand.

The study of wood trade flows[1] is indispensable to understand and to analyze these issues. It mainly relies on a set of models - hereafter

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[1] We define a wood trade flow as a quantity (mass or monetary) of a commercial wood-based product or waste moving from a departure point to an arrival point along a certain path. Commercial wood-based products include raw material, such as industrial roundwood or fuelwood, and transformed materials, such as pulp and paper products or sawn wood.

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referred to as “wood trade flow models” - that aim to represent wood trade flows and their dynamics. They deal with a variety of wood products, for example lumber (Johnston and van Kooten, 2017), fuelwood (Raunikar et al., 2010), wood pellets (Johnston and van Kooten, 2016), paper and pulp (Zhu and Buongiorno, 2002; Tang et al., 2015), or wood wastes (Müller et al., 2004; Szichta et al., 2022). They consider various spatial scales raging from global (Raunikar et al., 2010) to macro-regional (Kallio et al., 2006), national (Caurla et al., 2013), or subnational (Müller et al., 2004). They also consider different geopolitical contexts, such as the European Union (Kallio et al., 2006) or North America (Johnston and van Kooten, 2017). These models highlight factors[2] ranging from tariff barriers (Zhu et al., 2001; Solberg et al., 2010) to domestic forest resource endowment (Zhang and Li, 2009; Vu et al., 2020), efforts against illegal logging (Moiseyev et al., 2010), or forest conservation programs (Kallio et al., 2006). Some works have investigated certain sub-categories of wood trade flow models. For instance, some previous works introduce an overview, a typology, or a historical perspective of the literature on Forest Sector Models (Caurla, 2013; Latta et al., 2013; Riviere and Caurla, 2020; Riviere et al., 2020). However, these reviews have not covered the whole range of models for wood trade flows, such as gravity models (Buongiorno, 2016; Vu et al., 2020) or material flow analysis (Hekkert et al., 2000; Müller et al., 2004; Szichta et al., 2022). Yet these other models are also interesting because they explore a wider range of applications with wood trade flow models. To our knowledge, no complete and comprehensive review of all wood trade flow model objectives, nor of the wood trade flow factors they consider, is available. In this study, we conducted a meta-analysis on wood trade flow modeling concepts to fil this gap.

The present meta-analysis of wood trade flow models relies on a strong hypothesis. We assume that wood trade flow models with very different modeling objectives, such as policy analysis or forecasting (Buongiorno, 1996, 2016; Riviere and Caurla, 2020), are based on a wide diversity of wood trade flow factors. Indeed, when papers simultaneously address various materials flows, they cite socio-economic factors such as domestic income and economic size (Krausmann et al., 2009; Steinberger et al., 2010; Schandl et al., 2018), technological changes (Kovanda and Hak, 2008; Wood et al., 2009; Steger and Bleischwitz, 2011), or urbanization dynamics (Moynihan and Allwood, 2012; Pauliuk et al., 2013; Wang et al., 2014). Our study provides the first comprehensive overview and categorization of objectives of wood trade flow models and of factors, considering and highlighting gaps requiring future research in forest sector modeling.

2. Materials and method

Our aim was to identify and categorize the different modeling objectives of wood trade flow models and their factors. To do so, we performed a meta-analysis on the modeling concepts of 499 publications in English and French about wood trade flow modeling, published between 1972 and early 2022. We analyzed five document types: articles, reviews, books, book chapters, and conference papers. About 55% of the 499 documents were published in 20 journals, primarily forest science journals[3] (Fig. 1). The non-forest science journals are economics and environmental science journals. Five journals, namely *Forest Policy and Economics*, the *Journal of Forest Economics*, the *Forest Product Journal*, the *Canadian Journal of Forest Research*, and *Forest Science*, account for a third of the corpus. This corpus was retrieved in December 2021 from the Scopus database (Ballew, 2009), using a search query on document abstracts, titles, and keywords. The search query used Boolean operators to combine 171 modeling methodology keywords (such as “forest sector model”, “gravity model*”, or “material flow analysis”), 162 thematic keywords (such as “timber”, “wood”, “trade”, or “export*”), and 20 Scopus parameters that refine results. Supplementary materials 1 and 2 each give the method used to build the search query and to apply it. The complete bibliographical references of the 499 publications are listed in supplementary materials 3. We conducted a bibliometric analysis on this literature using the R package “bibliometrix” (Aria and Cuccurullo, 2020). Supplementary materials 4 provide the R script for the bibliometrix analysis.

We analyzed the conceptual structure of the literature by performing a factorial analysis of the corpus (Fig. 2). This method extracts a thesaurus of authors' keywords, and performs a hierarchical classification of the corpus (Fig. 3) based on the same keywords. These two methods are basically a way to reduce the high dimensionality of such a corpus of literature into factors, and to suggest hierarchies of factors according to their contribution to the variability among the papers constituting the corpus. Figs. 2 and 3 are graphical representations of the variability of the keywords, and of the correlation between the keywords. The “bibliometrix” package directly produces these images. But other factorial analysis packages such as “factominer” (Husson et al., 2016) could also produce the same images when applied to the contingency tables produced by “bibliometrix”. To our knowledge, what is unique to “bibliometrix” is the possibility to interpret the conceptual structure of a body of literature into an epistemological structure. The filiation of concepts represents the evolution of modeling concepts into new concepts over time (Fig. 4). The filiation between the most relevant papers[4] in the literature appears in Fig. 5.

The factorial analysis and the hierarchical classification produced contingency tables of keywords which we regrouped into statistical categories. We interpreted these categories as modeling objectives and identified keywords on wood trade flow factors. We could group the factors shaping wood trade flows considered in wood trade flow modeling, according to our understanding of the epistemological structure of the corpus. Following the nuances expressed in the various documents, some keywords can appear both as model objectives and as wood trade flow factors. Some documents may belong to several categories. We grouped the categories under meaningful labels,[5] and for each we computed the percentage of associated documents and the associated standard deviation.

The main methodological drawback of such a meta-analysis is that a degree of automation induces a certain loss of references. In the present case, the import procedure of “bibliometrix” discards some references from the bibliographic files exported from the Scopus database. Only $n = 283$ references out of $N = 499$ could be perfectly imported and analyzed in their entirety. Not all the references within the Scopus database contain author keywords. For many references, formatting anomalies are inherited from what was originally imported or keyed into the Scopus database. This disrupts the complete importation of all fields beyond the title, the date and the authors. Consequently, 216 references were not analyzed. As a result, we imported complete data for 283 references forming the sample (the domain of validity of the analysis), and performed the analysis on them. Conversely, there was no certainty that the variability and distribution of keywords within the sample would be similar for the remaining 216 references, the variability of which was unknown. Thus, the remaining 216 references are a domain of extrapolation, that is, a domain that lies beyond the observation range but on which we can infer the properties of the domain of validity.

[2] We define wood trade flow factors as physical quantities and determinants studied in wood trade flow modeling.

[3] Based on the journal categories of the Journal of Citation Reports[tm] of Clarivate Analytics.

[4] In the “histPlots” function from the “bibliometrix” R package used to plot historical direct citation networks as in Figure 5, the most relevant n documents are the n documents that (1) are the most cited locally, that is, that are the most cited in the body of literature, or (2) the documents that most cite documents in the body of literature.

[5] The list of author keywords for each category is provided in supplementary materials 5.

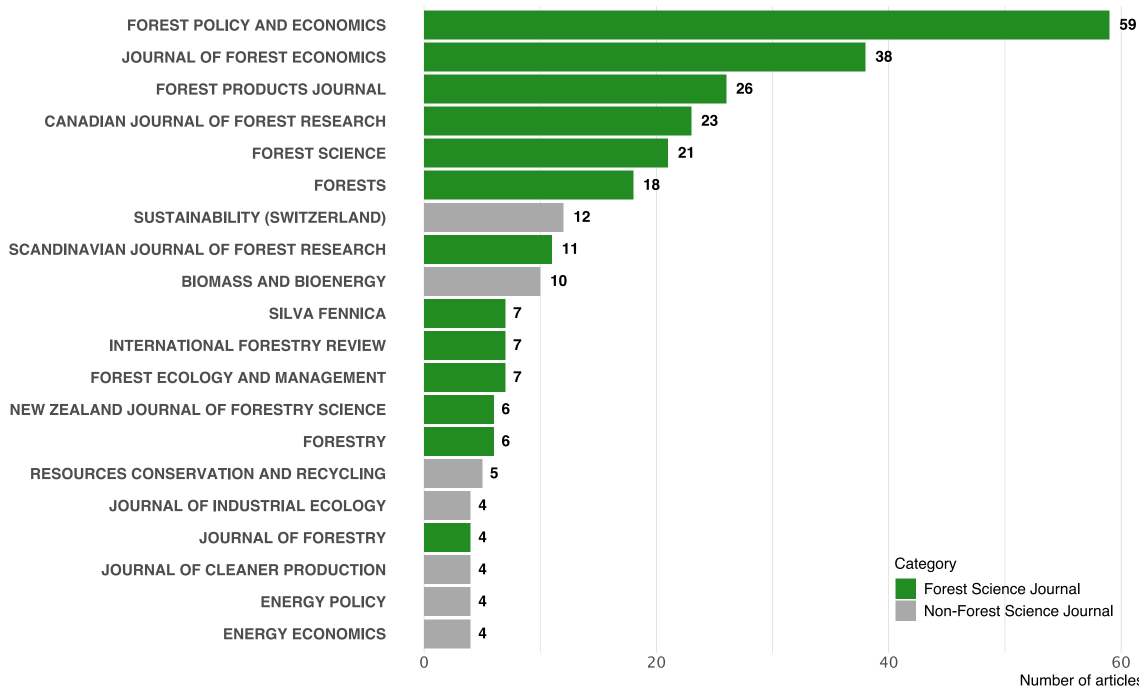

Fig. 1. Number of articles in the body of literature by journal. Only the 20 most represented journals in the body of literature are shown. Forest science journals are displayed in green, non-forest science journals in gray. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Therefore, prediction intervals express the uncertainty of the results. The intervals widen when the size of the domain of extrapolation increases. Various model objectives and wood trade flow factors have more or less prevalence within the literature on wood trade flow models. To help our interpretation, we computed odds ratios for each possible pair of categories in comparison to a random situation where every model objective or wood trade flow factor would have an equal presence in the literature.[6]

For the odds ratio of A occurrence vs B occurrence:

- OR = 1 the odds of A or B occurrence are equivalent;
- OR < 1 the odds of A occurrence are lower;
- OR > 1 the odds of A occurrence are higher.

3. Results

3.1. Objectives of wood trade flow modeling

The epistemological structure of our literature base shows that since 1972, three modeling objectives have mostly influenced wood trade flow models: models to understand trade mechanisms, models to forecast trends, and models to explore or simulate the effects of various policies (Figs. 2 and 3). Models investigating trade mechanisms constitute around 5% of our body of literature. Forecasting models constitute 9%. Policy-oriented models appear in 99% of the literature (Table 1). The proportions of models that aim to analyze trade mechanisms or to forecast are not significantly different, according to the 95% prediction intervals (Table 1). This result indicates that policy analysis purposes and, to a lesser extent, trade mechanism analysis and forecasting purposes, have mostly been the motivation behind wood trade flow models. Trade mechanism analysis and forecasting purposes appeared in similar proportions in our body of literature. Among the 283 documents processed, 40 documents (around 14% of the body of literature) use wood trade flow models for at least two objectives out of three.[7] One publication (0.4% of the literature) uses wood trade flow models for both forecasting and trade mechanism analysis. Thirteen publications (4.6% of the literature) use them for both policy and trade mechanisms analysis. Twenty-six publications (9.2% of the literature) use them for both policy analysis and forecasting.

Policy-oriented models represent 99% of the literature. They can be grouped into three subcategories: models that address economic disruptions, models that address environmental issues, and models that address energy, welfare and policy issues. Almost 38% of the literature address major economic disruptions, such as the rise of China or illegal logging (Table 1). Environmental issues such as climate change or deforestation concern about 40%. Models addressing energy, welfare, or trade policies constitute 49% of the literature. The proportions of each subcategory included in the policy analysis objective are not significantly different, according to the 95% prediction intervals (Table 1). These three main sets of issues appear equally in the literature. In our body of literature, about 23% of the policy-oriented models belong to two of these subcategories, suggesting a certain degree of overlap between these three subcategories.

Odds ratios show that, since 1972, wood trade flow models have been used almost 20 times more to study policies than to understand trade mechanisms, and used around 10 times more to study policies than for forecasting (Fig. 6). On the other hand, wood trade flow models have been used for trade mechanism analysis and for forecasting in similar proportions, as is the case for every pair of subcategories of the policy analysis objective. This is consistent with our previous results.

3.2. Wood trade flow factors

Wood trade flow models have presented a narrow set of four

[6] See Katerndahl and Lawler (1999) for an example of the use of odds ratios in medicine.

[7] This explains why the sum of the proportions of the different model objectives exceeds 100%.

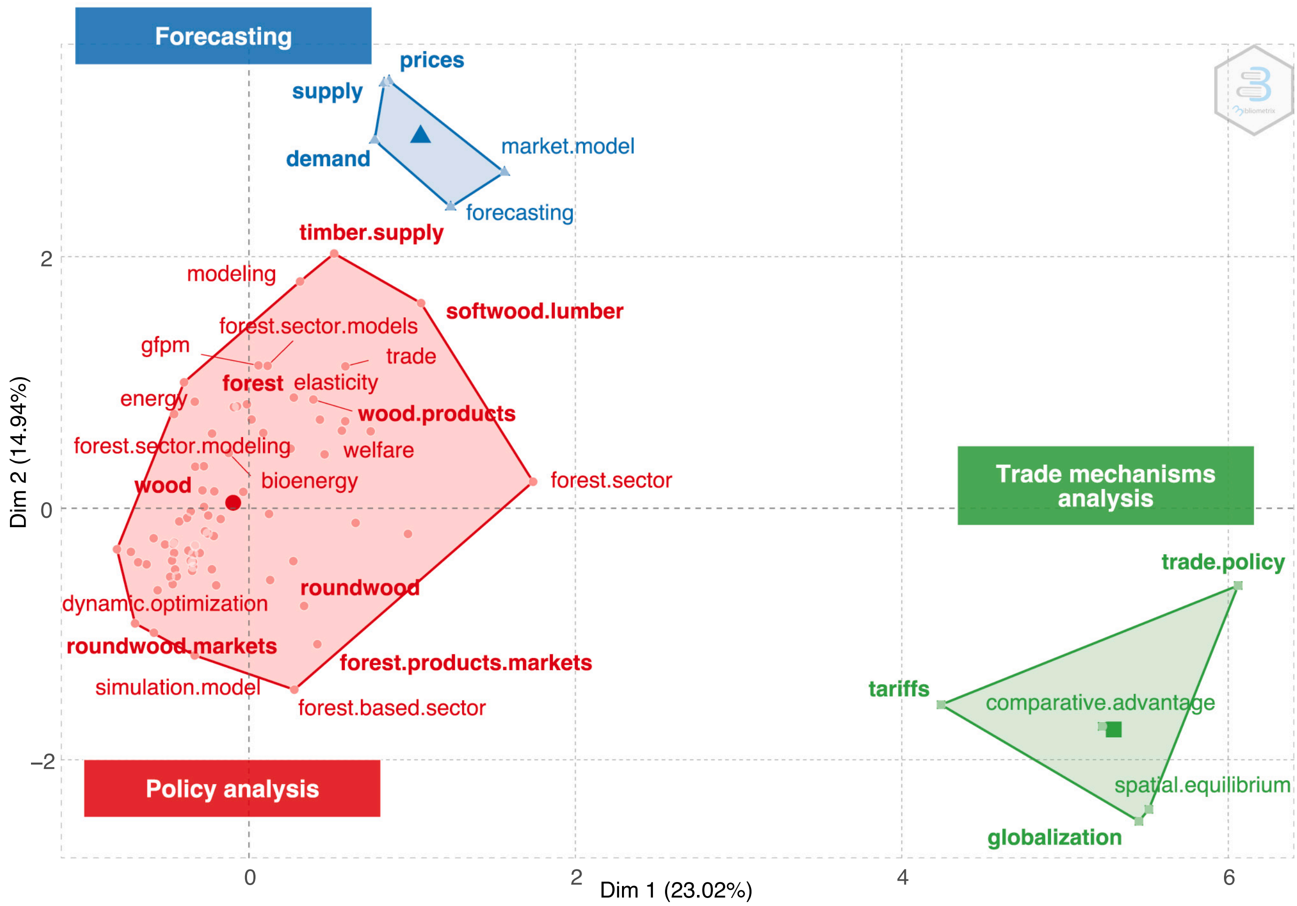

Fig. 2. Conceptual structure map of the literature resulting from a factorial analysis on author keywords using the "bibliometrix" R package (Method: MCA). Author keywords are organized into three clusters that best separate the modeling objectives: policy analysis (red cluster), forecasting (blue), and trade mechanism analysis (green). Keywords relative to wood trade flow factors are in bold. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

categories of factors:

- price factors,
- the interdependency of production factors,
- policy factors,
- stock and trade quantity factors.

Price factors, such as prices of traded products, tariff barriers, or exchange rates, account for more than 6% of the literature (Table 2). The interdependency between production factors, such as capital, labor, or land, relate to more than 10% of the literature.[8] Almost 15% of the literature relates to policy factors defining trade policies and regulations, or forest conservation policies and regulations, or forest certifications. Stock and trade quantity factors, such as import-export quantities, supply-demand quantities, or quantities of a specific wood product, appear in almost 50% of the literature. The odds of price factors vs the interdependency of production factors, and of the interdependency of production factors vs policy factors, are not significantly different in proportion, as shown by the 95% prediction intervals (Table 2). This indicates that, regardless of their objective, wood trade flow models have mostly considered stock and trade quantity factors to study these flows and their dynamics. Conversely, they have placed less emphasis on price and policy factors, and on the interdependency of production factors. All in all, these four categories of factors cover about two-thirds of the body of literature. This suggests that wood trade flow modeling has also studied other wood trade flow factors that do not explain the variability observed in the body of literature.

The stock and trade quantity factors category can be divided into three subcategories, depending on how models approach such factors: supply-demand quantities, import-export quantities, and quantities of a product. Supply-demand quantity factors relate to the production and consumption of wood products, including domestic supply, demand, imports, and exports. In contrast, import-export quantity factors refer only to the quantities traded between regions. The last subcategory refers to the differentiation of different wood products and their specificity by wood trade flow models. These three subcategories account for respectively 16%, 18% and 31% of our body of literature (Table 2). The proportions of import-export and supply-demand quantity factors are not significantly different, as suggested by the 95% prediction intervals (Table 2). This suggests that wood trade flow modeling has studied stock and trade quantity factors by differentiating wood products slightly more than by differentiating flows of imports and exports or supply and demand.

On the one hand, the odds ratios indicate that wood trade flow modeling has considered approximately 7, 5, and 3 times more factors of stock and trade quantity than price factors, policy factors, and the interdependency of production factors. Wood trade flow models have considered twice as many policy factors as price factors (Fig. 7). On the

[8] As shown in supplementary materials 5, this category comprises keywords such as "timber market" or "forest product markets". We interpret this set of "market" keywords as a category of factors related to the production process of wood products, that is, factors of production.

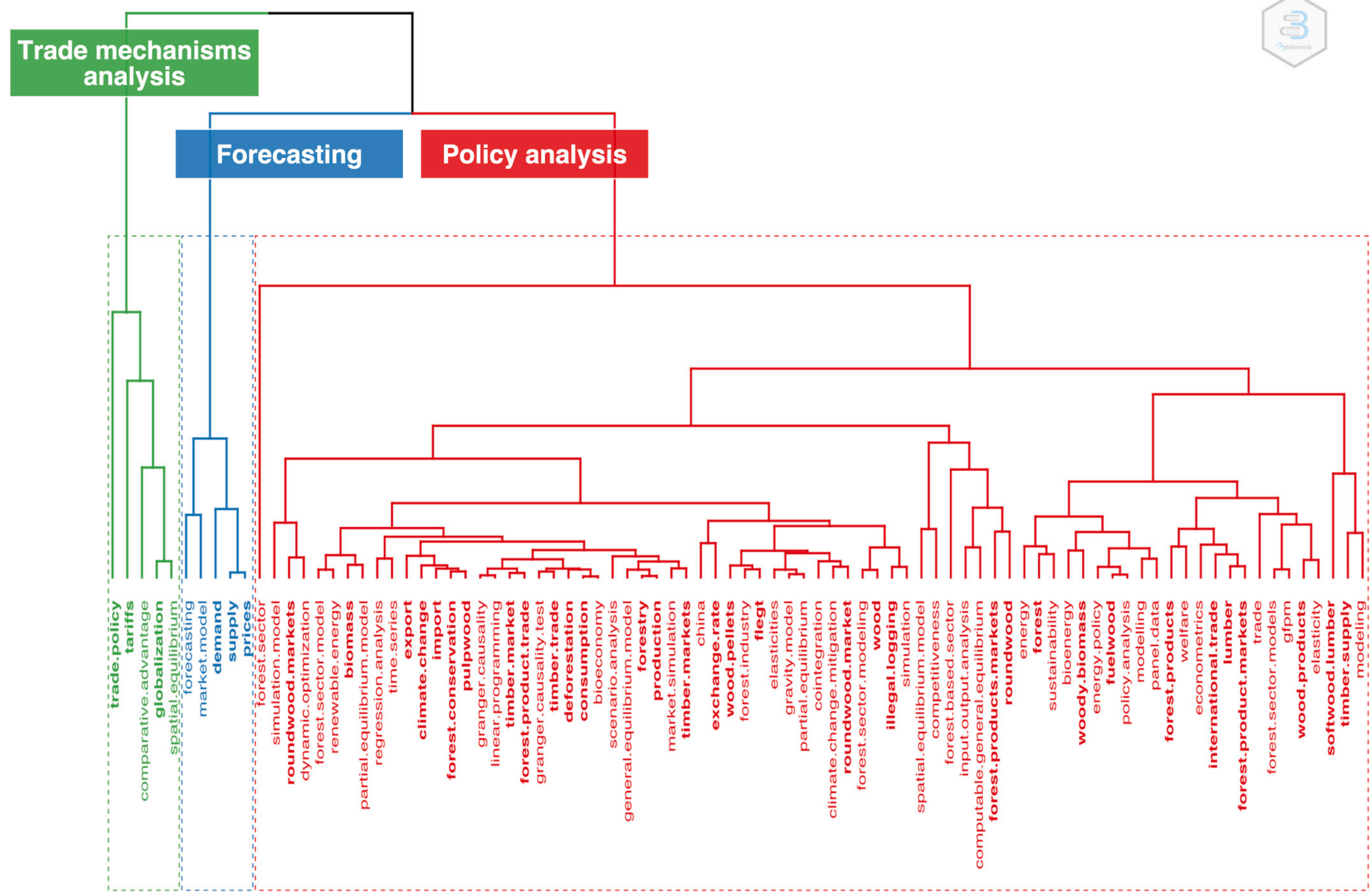

Fig. 3. Topic dendrogram resulting from a hierarchical classification of author keywords extracted from the literature using the "bibliometrix" R package. Author keywords are organized into three clusters that best separate the modeling objectives: policy analysis (red cluster), forecasting (blue), and trade mechanism analysis (green). Keywords relative to wood trade flow factors are in bold. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

other hand, wood trade flow models have studied price factors vs the interdependency of production factors equally, in the same way as the interdependency of production factors vs policy factors. Among the three subcategories of stock and trade quantity factors, models have segregated these factors slightly more according to products than according to supply-demand quantities or import-export quantities. They have studied supply-demand and import-export quantity factors in similar proportions. Overall, this corroborates our previous results.

4. Discussion

This meta-analysis does not capture the fine details and nuances. When also looking at the evolution of wood trade flow modeling concepts (Fig. 3), we realize that the very earliest works were either exploring wood trade through macroeconomics and supply-demand theory, or were exploring how forest policies might influence trade through forest management at different scales (Buongiorno, 1978; Bare et al., 1984; Uutela, 1984; Ghebremichael, 1989; Buongiorno, 1996; Lin et al., 1996; Volin and Buongiorno, 1996; Buongiorno et al., 1998, 2000; Trømborg et al., 2000). They were also exploring how issues external to the forest (regional, national, or international demand, price, etc.) might impact the demand for forest products (e.g., Buongiorno, 1978). The aims of the models or the use of their simulations have adapted in order to address the evolutions of sociopolitical concerns, along with the interests of the time. Meanwhile, the core modeling concepts have been remarkably stable and have remained deeply rooted in traditional economic theory and econometrics. From the early attempts to model wood trade flows, approaches have relied on econometric methods or computable general and partial equilibria to study forest product markets, in the light of economic concepts such as comparative advantage. While this modeling objective is still pursued in contemporary wood trade flow modeling,[9] wood trade flow models now address issues that have emerged since the 1990s. Since wood trade flow models have a strong policy analysis orientation, their focus has evolved in relation to political and societal debates. The modeling concepts established in the 1970s have evolved in response to the rise of environmental issues such as climate change (Sohngen and Mendelsohn, 1998; Sohngen et al., 2001; Jonsson et al., 2021) and forest conservation (Linden and Uusivuori, 2002; Kallio et al., 2006; Zhang and Li, 2009). They have also evolved in response to bioenergy and welfare concerns (Raunikar et al., 2010; Buongiorno et al., 2011; Johnston and van Kooten, 2016). This evolution has also been observed in the case of forest sector models (Riviere and Caurla, 2020).

Our initial hypothesis was that over the period, wood trade flow models with different modeling objectives would rely on a wide diversity of wood trade flow factors. Contrary to our hypothesis, we found that all three main modeling objectives, that is, understanding trade mechanisms, forecasting trends, and policy analysis, have considered only four categories of factors since 1972: price factors, the interdependency of production factors, policy factors, and stock and trade

[9] Notably to study the rise of China in the global forest sector and international trade of forest products.

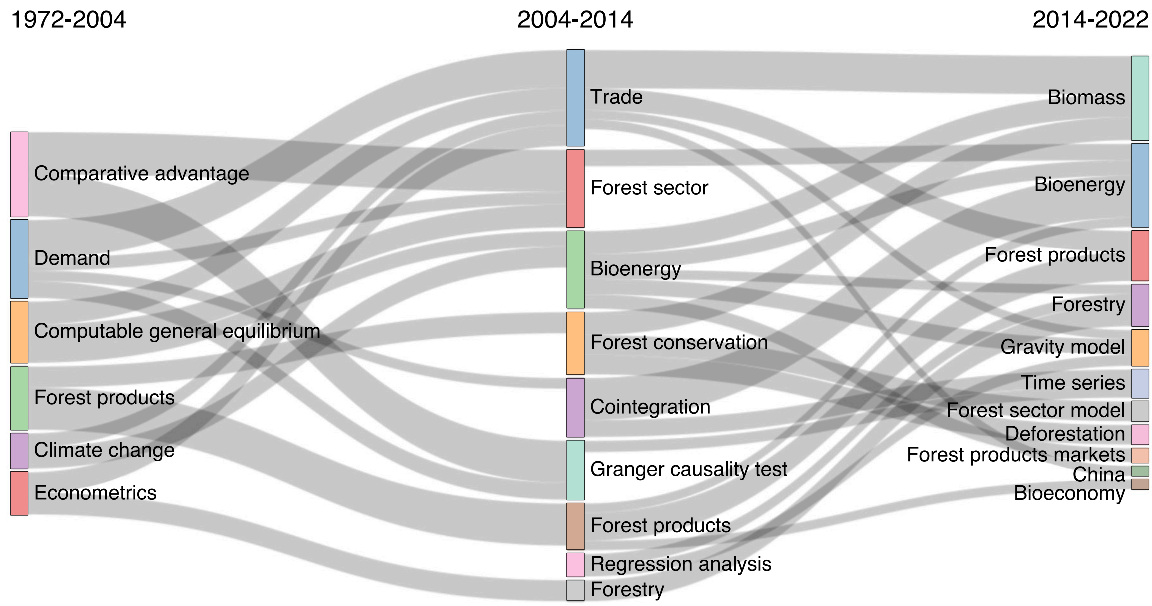

Fig. 4. Epistemology of the themes used in wood trade flow modeling. The larger the rectangle, the more a theme influences the corresponding time slice. The thicker a link between themes (in gray), the stronger the parentage is between subsequent themes. Between 1972 and 2004, the main themes were comparative advantages, demand, general equilibrium, forest products, econometrics, and already climate change. From 2004 to 2014 they shifted to trade, forest sector, bioenergy, forest conservation, and regression analysis. After 2014 new themes such as gravity model, deforestation, China and bioeconomy became prevalent. The "bibliometrix" R package produced this figure.

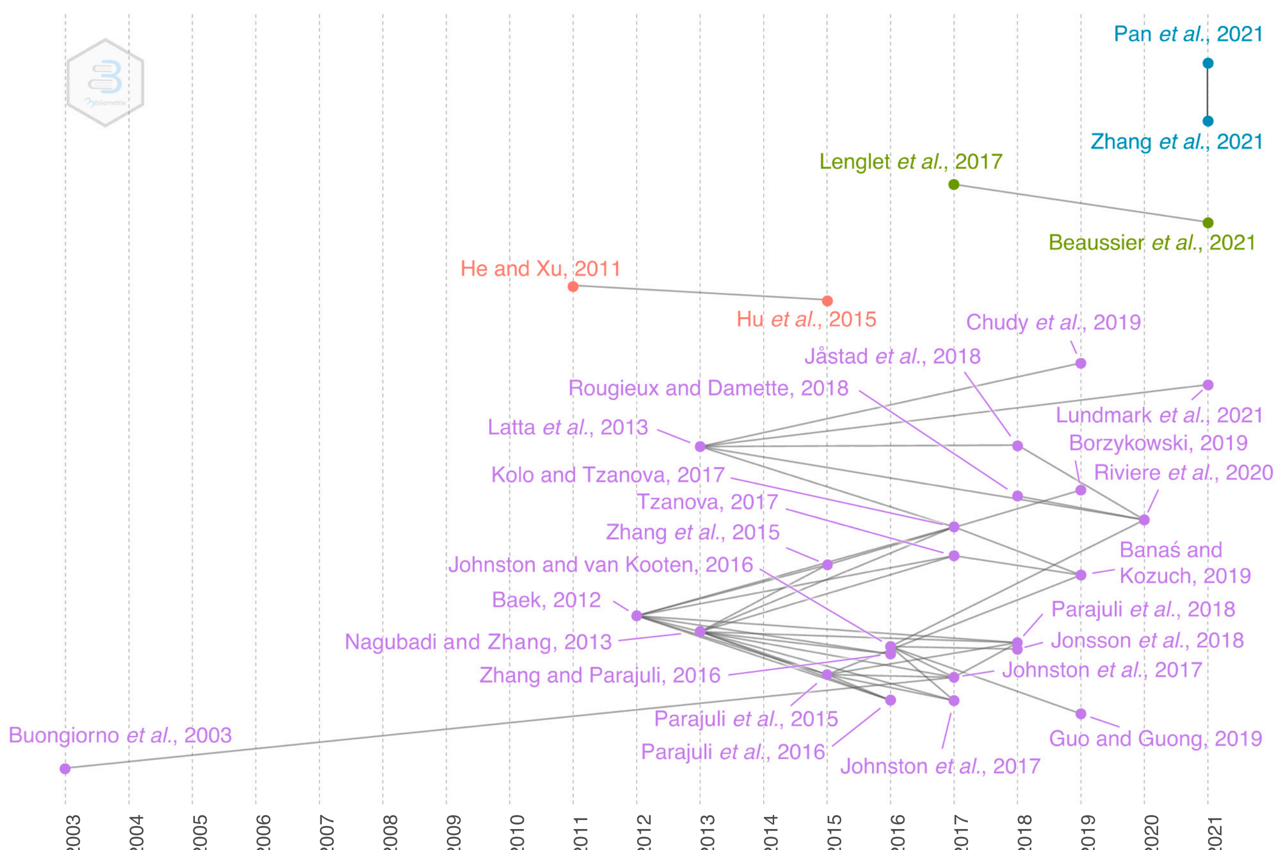

Fig. 5. Epistemology of the main papers themselves, through the arborescence of their citations. Each node represents a publication. Two nodes are connected if the recent publication cites the older publication. For readability reasons, only the thirty most relevant nodes are displayed. The "bibliometrix" R package produced this figure.

Table 1
Occurrence, proportion, and associated standard deviation of documents by modeling objective and policy-related objective.

Model objectives	Occurrence	Proportion (in %)*	Standard deviation (in %)*	Prediction interval at 95% (in %)**
Trade mechanisms analysis	15	5.3	1.3	[2.7; 7.9]
Forecasting	27	9.5	1.7	[6.1; 13.0]
Policy analysis	280	98.9	0.6	[97.7; 100.1]
(Economic disruptions)	107	37.8	2.9	[32.2; 43.5]
(Environmental issues)	114	40.3	2.9	[34.6; 46.0]
(Energy, welfare, and trade)	139	49.1	3.0	[43.3; 54.9]

* We computed proportions and standard deviations for a sample size $n = 283$.
** We computed prediction intervals at 95% for a sample size n = 283 and a domain of extrapolation size of N-n = 216 (where N = 499 is the size of the complete body of literature).

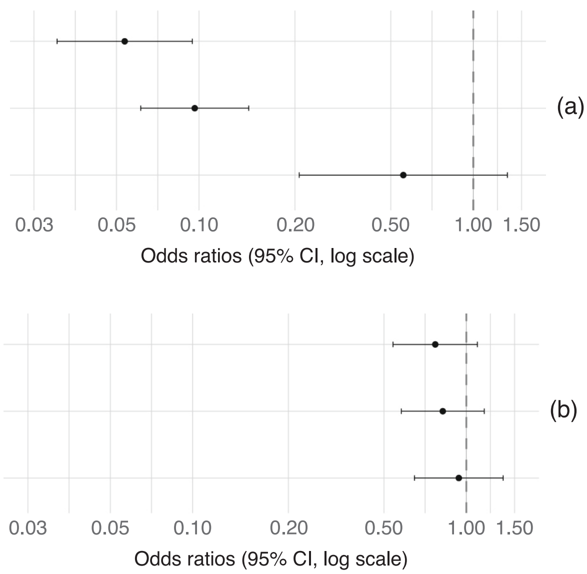

Fig. 6. Odds ratios for each pair of modeling objectives (A) and for each pair of policy-related objectives (B), with 95% prediction intervals.

Table 2
Occurrence, proportion, and associated standard deviation of documents by category of wood trade flow factors and by category of stock and trade quantity factors.

Wood trade flow factors	Occurrence	Proportion (in %)*	Standard deviation (in %)*	Prediction interval at 95% (in%)**
Price	18	6.4	1.5	[3.5; 9.2]
Interdependency	30	10.6	1.8	[7.0; 14.2]
Policy	41	14.5	2.1	[10.4; 18.6]
Stock and trade quantity	139	49.1	3.0	[43.3; 54.9]
(Supply-demand quantities)	46	16.3	2.2	[12.0; 20.6]
(Import-export quantities)	51	18.0	2.3	[13.5; 22.5]
(Quantities of a product)	88	31.1	2.8	[25.7; 36.5]

* We computed proportions and standard deviations for a sample size $n = 283$.
** We computed prediction intervals at 95% for a sample size n = 283 and a domain of extrapolation size of N-n = 216 (where N = 499 is the size of the complete body of literature).

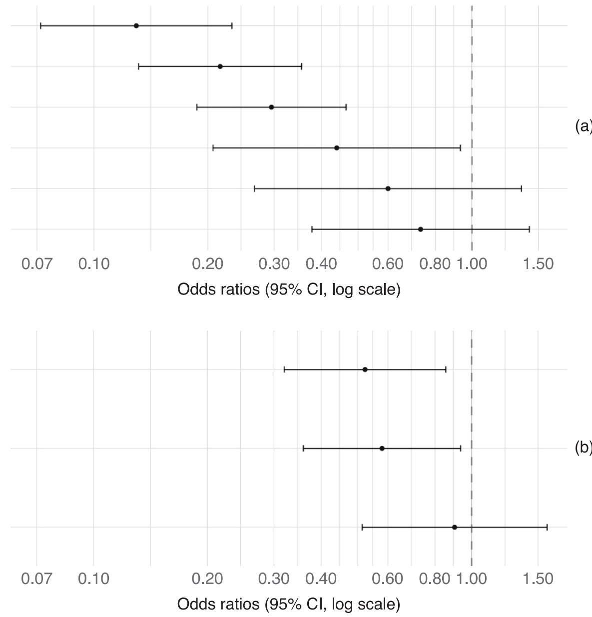

Fig. 7. Odds ratios for each pair of wood trade flow factor categories (A) and for each pair of stock and trade quantity factor subcategories (B), with 95% prediction intervals.

quantity factors.

We found that wood trade flow models almost systematically have a basis in policy analysis and, to a lesser extent, forecasting or understanding trade mechanisms. Our results have also shown a certain degree of overlap between the three main modeling objectives. This suggests that wood trade flow models may have been used for dual objectives, such as policy analysis and forecasting or policy analysis and understanding of trade mechanisms. These results are consistent with the findings of previous reviews on forest sector models (Latta et al., 2013; Riviere and Caurla, 2020; Riviere et al., 2020) while extending their conclusions to all wood trade flow models. Forest sector models were among the first attempts to model wood trade flows, along with econometric studies (Buongiorno, 1978; Solberg, 1986; Buongiorno, 1996), and still contribute substantially to the literature on wood trade flow modeling (Riviere and Caurla, 2020; Riviere et al., 2020). We can assume that other wood trade flow modeling methods emerged in the wake of the initial objectives of forest sector models, that is, mostly policy analysis (Riviere and Caurla, 2020), but also forecasting and trade mechanism analysis (Latta et al., 2013; Riviere et al., 2020).

The policy analysis objective of wood trade flow models contains three sub-objectives: economic disruption assessments, analysis of environmental issues, and the study of energy, welfare and policies issues. These three research strands have also been observed for forest sector models (Latta et al., 2013; Riviere et al., 2020). The study of economic disruptions refers to one of the primary objectives of wood trade flow analysis, that is, the study of forest product markets (Buongiorno, 1996; Latta et al., 2013; Riviere et al., 2020).

We found that wood trade flow models have mostly relied on a narrow set of four categories of factors to represent wood trade flows since 1972: price factors, the interdependency of production factors, policy factors, and stock and trade quantity factors. The perception of the main factors for wood trade flow models has changed very little since the 1970s. This may hinder the ability of the models to address the new problems that have emerged since then that they are supposed to address. This result is consistent with Riviere et al. (2020), who stated that since the conception of forest sector models, "[forest sector models'] structure and target [have remained] the same". Three factors may explain this inertia. First, the concepts on which wood trade flow modeling relies have evolved but remain fundamentally tied to the concepts originally used in the 1970s (see Fig. 4 and comments above). Second, wood trade flow models have been developed within a rather limited research community that has relied on early modeling efforts (Riviere and Caurla, 2020). This is visible in the historical direct citation network of the thirty most relevant documents in our body of literature (Fig. 5), where documents are primarily structured into one cluster of citations, with the work of Buongiorno et al. (2003) as its basis. Third, historically, most wood trade flow models rely on forest inventory, trade, and macroeconomic data for calibration, simulations, or parameter estimations. This reliance may prevent any paradigm shift among wood trade flow models. The fact that data on other wood trade flow factors may be scarce does not help. For example, in the case of forest sector models, the frequent lack of firm-level data prevents the emergence of a new trade theory, such as Krugman's (Fujita et al., 2001) or Melitz's (Melitz, 2003), to challenge the use of Samuelson's trade theory (Samuelson, 1952), which still underlies many forest sector models (Riviere and Caurla, 2020). Hence, we assume that including new factors in wood trade flow models is costly and requires major changes to the model structure and paradigm. Some attempts have used model coupling in order to extend the scope of wood trade flow models, e.g., Lenglet et al. (2017) and Beaussier et al. (2022) who coupled the French Forest Sector Model with a material flow analysis and a life cycle assessment, respectively, but show some limits in terms of tractability and operationality.

Beside the world of trade flow models, wood is one of the main materials for construction, along with metals and minerals. Other domains such as regional science, urban metabolism, and domestic material consumption (DMC)[10] routinely study the flows and consumption of various materials, including wood materials. They link energy and material consumptions and trade flows to factors such as GDP and income elasticities (e.g., Krausmann et al., 2009; Steinberger et al., 2010; Schandl et al., 2018), as the classical wood trade flow models do for their own sector (e.g., Buongiorno, 1978; Buongiorno et al., 1998; Buongiorno, 2016).[11] With GDP and income, these approaches account for factors that are already taken into account in wood trade models, but they also point to technological change as a factor that affects material and energy consumption (Kovanda and Hak, 2008; Wood et al., 2009; Steger and Bleischwitz, 2011). Technological change also appears in forest sector models through input-output coefficients (Buongiorno, 1996; Caurla et al., 2010; Buongiorno and Zhu, 2015). Regional science, urban metabolism, and DMC approaches also account for other factors that are not considered in wood trade flow modeling to study material consumption and flows. They directly connect factors such as population densities, land availability, and stocks of manufactured materials - in other words, the urbanization process - to the flows and consumption of construction materials: metals (such as steel), minerals (such as concrete) and biomass (such as wood).

The meta-analysis of regional science, urban metabolism, and DMC approaches is beyond the scope of this study, but at least 36 significant contributions from these disciplines (listed in supplementary materials 6) suggest that urbanization is a critical factor to understand or to model uses and consumption of materials such as minerals, metals, and wood. Specifically, the growth of manufactured capital stocks, which include buildings, infrastructure, and durable goods, as well as their maintenance and operation, are found to be a major but neglected factor of material and energy consumption (Müller, 2006; Fernández, 2007; Hu et al., 2010; Huang et al., 2013; Wiedenhofer et al., 2015; Krausmann et al., 2017, 2018; Wiedenhofer et al., 2019; Deetman et al., 2020). Globally, more than half of the materials extracted or produced directly increase the manufactured capital stocks (Krausmann et al., 2017, 2018; Wiedenhofer et al., 2019). Urbanization processes and dynamics form a body of factors that govern mineral and metallic material flows. The same group of studies always considers wood as one of the main building materials (Müller, 2006; Bergsdal et al., 2007; Hu et al., 2010; Fishman et al., 2014; Tanikawa et al., 2015; Kleemann et al., 2017; Krausmann et al., 2018; Deetman et al., 2020). These studies also show that the use of materials (including wood) in the building stock varies across contexts and over time. Material consumption differs between rural and urban areas (Huang et al., 2013; Deetman et al., 2020), between emerging and industrialized economies (Krausmann et al., 2017, 2018), or between countries with contrasted timber construction traditions, as noted by Müller (2006) in the case of The Netherlands. Notable differences depend on the country under study. For instance, Tanikawa et al. (2015) note in their results that “approximately 70% of buildings in Japan are constructed from timber”. Bergsdal et al. (2007) explain that, in the Norwegian context, “85% of the current Norwegian dwelling stock is small houses, constructed almost exclusively with wood as the main building material”. Results from Fishman et al. (2014) also show that timber was the second most important construction material in volume terms for the material stocks of Japan and the United States in the early 21st century.

Although building stocks of all materials have been increasing since the early 20th century (Fernández, 2007; Krausmann et al., 2017, 2018), the share of each material in the stock of manufactured capital has changed. For industrialized countries and at a global scale, wood was the main building material in the early 20th century but its share of the manufactured capital stock has declined in favor of concrete, which is currently the main building material used for construction (Bergsdal et al., 2007; Tanikawa et al., 2015; Kleemann et al., 2017). Some works explain these changes in material consumption in a theoretical way, suggesting an evolution of material and energy consumption over time according to 3 or 4 different phases of urbanization (Fernández, 2007; Véron, 2006; Dumont, 2018), with generally one phase of rapid urbanization that leads to a sharp increase in material consumption. This multi-phase “urban transition” directly derives from the notion of “demographic transition” (Dumont, 2018), which raises the question of whether the factor pointed to in these studies is purely urban or whether it is instead a demographic dynamic hidden behind the urban phenomenon.

For Steinberger et al. (2010), “the most significant explanatory variable is always population [...] indicating that material flows are exactly proportional to population”. They also find that materials are moderately income elastic, with, interestingly, biomass (including wood) and construction materials being much more inelastic than minerals, generally. This is in contrast with many wood trade modeling approaches which classically use GDP or GDP per capita as critical factors, and seldom include population as a direct driver. Steinberger et al. (2010) propose a generic model: Domestic Material Consumption (DMC) = f(Population, Income, Area, Climate); where population is the stronger factor in all cases, but where real differences appear between materials.[12] Income is a big influence only for fossil fuels and ores/industrial minerals, climate influences fossil fuel consumption but not material consumption, and land availability has a strong influence on biomass and ores/industrial minerals.

This last point is very interesting because for forest products and mining products, land area per capita is almost a proxy for the quantity of potential resources, potential production, and stock. Important nuances derive from the fact that for some materials such as wood or construction minerals, the exported quantities are considerably smaller than what is produced and consumed locally. Even so, such purely

[10] DMC can be defined as domestic extraction (or production) plus imports minus exports (Fishman et al., 2014).

[11] See also Nasrullah et al. (2020) and Vu et al. (2020) for two additional examples of the use of GDP as a wood trade flow factor in gravity models.

[12] Steinberger et al. (2010) also show that while the trajectories of some groups of materials seem to be correlated -in particular, the trajectories of fossil fuels, construction minerals, and ores/industrial minerals- some, like biomass, stand out.

empirical works[13] could propose models where wood trade flows would mostly appear as Wood Trade Flows = f(Population, Land Availability), which is seriously in contrast with the classical wood trade models which almost all stem from pure economic theory.

Extending regional science and DMC studies, other empirical and urban planning works strongly link the stocks and flows of wood, iron (and steel), and cement (and other minerals) to urban dynamics, the time evolution of cities (Tanikawa and Hashimoto, 2009), their structure and organization (Tanikawa et al., 2002, 2004), or in more general terms to the concept of "urban metabolism" (Ferrão et al., 2014; Inostroza, 2014). The fact that city growth and urbanization processes are significant users of wood, as they are of other metals and minerals, is demonstrated at the city level. But it is not clear that this would apply at other scales or lead us to believe that such urbanization processes would be significant factors of wood trade flows at the national, macro-regional, or even global levels. At another level of analysis, many other works on steel (Ghosh, 2006; Huh, 2011; Oda et al., 2012; Moynihan and Allwood, 2012; Pauliuk et al., 2013; Hattori et al., 2014; Liang et al., 2014; Yellishetty and Mudd, 2014) clearly point to the fact that demographic evolutions, human population concentrations and urbanization of societies and of landscapes are critical drivers of steel consumption and trade flows. What is demonstrated for steel could be also true for another structural material, such as wood.

These considerations raise the new question of whether urban dynamics are an important factor in wood trade flows. Are urban dynamics not already captured through factors currently considered in wood trade flow models, such as GDP or income? Do urbanization processes and dynamics encapsulate traditional wood trade flow factors, or do they constitute new and distinct dimensions? Is urbanization a new factor worth exploring to model wood trade flows? Scaling issues and clearer material versus cities and population ontologies are yet to be solved (Masucci et al., 2015), but we posit that for a better understanding of wood trade flows dynamics, it would be well worth specifically investigating to what extent population and urban metabolism could also be valuable factors to use in wood trade modeling. As it stands, only ten documents out of the 499 documents in our body of literature (2%) mention urbanization processes in their title, abstract or keywords, mostly for contextualization purposes.

By reducing the dimensions of our body of literature into a few factors that best explain the variability of the literature, our method may have limited the scope of our analysis and locked ourselves into a narrow window of interpretation. However, while lacking in precision by not capturing all the nuances, this method acts as a powerful tool to analyze finely the 499 documents in our body of literature and to rigorously structure its interpretation, albeit as a complement to a thorough reading of this literature. Such a method of analysis cannot do without a good knowledge of the documents, at the risk of being bound to a superficial analysis of the literature.

5. Conclusion

In summary, our work shows that, regardless of the application, the current literature on wood trade flow modeling has relied on the same narrow set of factors since the 1970s and neglected other possible factors that could have significant implications if taken in account. In the main, the literature rarely if ever uses certain factors that are considered in other scientific disciplines, such as regional science, urban metabolism, or domestic material consumption analysis. In particular, the central role of the growth of cities and of urbanization processes in shaping material trade flows remains unexplored overall by wood trade flow modeling. Compared to the perceptions in the last century of which forces drive forest sector economics, many new research questions have arisen, such as those linked to climate change, energy transition, bio-economy development, or globalization and large economic disruptions. New factors should be considered, in accordance with these changes.

CRediT authorship contribution statement

Valentin Mathieu: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Jean-Marc Roda:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Supervision.

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

The processing code and data used are provided in the attached Supplementary Materials file.

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Appendix A. Supplementary data

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[13] See also Weisz et al. (2006) and Krausmann et al. (2008) for additional empirical evidence of the role of population, population density and land availability in shaping biomass flows.

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