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Œconomia
History, Methodology, Philosophy

10-3 | 2020
Facts in Energy and Environmental Economics

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Electronic version
URL: https://journals.openedition.org/oeconomia/9418
DOI: 10.4000/oeconomia.9418
ISSN: 2269-8450

Publisher
Association Œconomia

Printed version
Date of publication: 1 September 2020
Number of pages: 521-553
ISSN: 2113-5207

Electronic reference
Miguel Rivière and Sylvain Caurla, “Representations of the Forest Sector in Economic Models”, *Œconomia* [Online], 10-3 | 2020, Online since 01 September 2020, connection on 10 September 2021. URL: http://journals.openedition.org/oeconomia/9418 ; DOI: https://doi.org/10.4000/oeconomia.9418

Representations of the Forest Sector in Economic Models

Miguel Rivière* and Sylvain Caurla**

Forest sector models encompass a set of models used for forest-related policy analysis. As representations of a complex human-environment system, they incorporate multiple facts from their target, the forest sector, which is usually understood as comprising forests, forestry and forest industries. Even though they pursue similar goals and display similarities, forest sector models show divergences in their representation of the forest sector. In this paper, we question and discuss the determinants behind the representation of facts in forest sector models, and try to highlight the reasons behind modelling practices. The forest sector's boundaries are often unclear, and it comprises facts of different natures for which dynamics take place on different time and spatial scales. As a result, modelling practices vary, and both empirical data and theory play varying roles in representing facts. Early models were developed in the 1970s and find their roots in traditional forest economics, the economics of natural resources, econometrics, but also transportation problems and system dynamics. Because they developed within a small but well-connected field, early efforts were influential in shaping current practices. Numerical simulation and scenario analysis are used as means of enquiry into model worlds: in that, forest sector models are a classical example of model use in economics, and they constitute a good example of how simulation models have been developed for decision-support purposes. Forest sector modelling is heavily influenced by its applied uses, and policy contexts shape both questions asked and how facts are introduced in scenario storylines. Understanding the determinants of modelling choices is necessary to ensure sound modelling practices. Forest sector models are now used to address issues wider than timber production. Practices turn to integration into multi-model frameworks to expand the boundaries of the system studied, but also towards the use of qualitative methods as new ways of representing facts, in particular deep changes that quantitative models may not be able to capture.

Keywords: forest economics, mathematical model, simulation model, prospective

*Université de Lorraine, Université de Strasbourg, AgroParisTech, CNRS, INRAE, BETA, miguel.riviere@agroparistech.fr
**Université de Lorraine, Université de Strasbourg, AgroParisTech, CNRS, INRAE, BETA, sylvain.caurla@inrae.fr
The authors would like to thank two anonymous reviewers and editors for their attentive help and insightful comments, as well as the editing team at Œconomia.

Les représentations du secteur forestier dans les modèles économiques

Les modèles de secteur forestier sont des outils utilisés dans le cadre d'exercices de prospective portant sur la filière forêt-bois. En tant que représentations de systèmes complexes, ces derniers incorporent de multiples faits issus de leur cible dans le monde réel, et qui peuvent être de différentes natures : dynamiques naturelles, procédés industriels, comportements économiques. Bien que poursuivant des objectifs semblables, ces modèles divergent dans le choix des faits représentés ainsi que dans celui des méthodes utilisées pour les représenter. Dans cet article, nous mettons en lumière les déterminants derrière les représentations du secteur forestier dans les modèles de filière, et remettons ainsi en perspective les pratiques de modélisation, notamment vis-à-vis de leur ancrage historique et méthodologique. Le secteur forestier constitue a priori un ensemble bien défini, mais ses limites exactes sont souvent floues. Elles varient selon la région du monde ou l'échelle spatiale considérée, et comprennent des dynamiques intervenant sur des échelles temporelles souvent disjointes. En résultent des choix de modélisation variés, utilisant à divers degrés théorie et données empiriques. Les premiers modèles furent développés dans les années 1970 et trouvent leur inspiration dans l'économie forestière et celle des ressources naturelles, mais aussi dans la dynamique des systèmes et les problèmes de transport optimal. Héritières d'une recherche au sein d'un champ restreint, les pratiques de modélisation du secteur forestier se sont fortement influencées entre elles, et l'empreinte des premiers modèles se retrouve encore aujourd'hui. La recherche repose sur des simulations numériques permettant d'explorer les futurs possibles par analyse de scénario, et le modélisateur observe le modèle afin d'en tirer des conclusions à propos du système représenté. En cela, les modèles de secteur forestier constituent un exemple archétypal de l'émergence de la simulation en économie comme procédé d'appui à la décision. En retour, le contexte dans lequel un modèle est développé a une forte influence sur les pratiques de modélisation, qu'il guide. Les modèles de secteur forestier sont aujourd'hui utilisés pour traiter de thématiques environnementales, et les pratiques se tournent vers une intégration de plus en plus forte avec d'autres modèles, permettant de repousser les limites du système représenté, mais aussi vers le recours à des méthodes qualitatives comme une nouvelle manière de représenter les faits difficiles à prendre en compte à l'aide de modèles quantitatifs.

Mots-clés : économie forestière, modèle mathématique, modèle de simulation, prospective

JEL: B16, C60, Q23

Economic analysis has a long tradition in forestry, illustrated by Faustmann's (1849) seminal work on the determination of an optimal harvesting criterion, still used and taught today (Amacher et al., 2010). While early developments focused on seemingly simple questions like "when should a tree be cut?," a significant part of the literature now uses large-scale models of the forest sector, or Forest Sector Models (FSM), to handle more complex questions. FSM are partial equilibrium, mathematical models of the forest sector enabling the determination of products prices, supply and demand quantities, solved numerically on computers due to their large size and the need for numerical values for expertise. They have applied uses in forecasting developments in timber markets and forest resources, evaluating forest policy and developing a better understanding of dynamics in the forest sector. The first models were developed to perform outlook studies in the 1970s, and, over time, FSM have been used to deal with questions related to climate change, energy production and environmental protection (Riviere, Caurla, and Delacote, 2020; Latta, Sjolie, and Solberg, 2013). As a result, they are often developed by teams of applied economists, mathematical engineers and forest scientists in laboratories with an applied research dimension, usually within the field of *forest economics*, and in collaboration with institutions having an interest in model use such as forest agencies or environmental NGOs.

The term of "representation" is often used to describe a model's relationship to the real world. The model can then substitute for its target as a tool for scientific enquiry and, by studying the model, one can draw conclusions about the real world by "surrogative reasoning" (Frigg and Nguyen, 2017; Gelfert, 2017; Gräbner, 2018). Even though debates exist on the definition and nature of "representation," in this article, we follow Morgan in her pragmatic approach focusing on how modellers develop and use models, assuming that "in making models, scientists form some kind of a representation of something in the economy" (Morgan, 2012, 24), in our case, the forest sector. The forest sector is often defined as comprising forestry and forest industries. As representations, FSM are bound to incorporate multiple facts from the forest sector, which we understand as any structure, process or behaviour within the system of interest. Forestry encompasses many natural facts such as forest biomass and its growth, multiple ecosystem services, or forest disturbances. On the other hand, forest industries include technological processes such as products manufacturing, recycling, transportation of products and by-products, etc. On both sides, economic behaviours are also found: timber harvesting and forest management choices for the former, products demand and trade for the latter. However, owing to the long history of forest sciences and to the diversity of forests and timber industries worldwide, FSM likely diverge in their representation of facts, even though they share some characteristics and similar purposes.

In this article, we seek to highlight the determinants of the representation of facts in FSM, that is to say, we want to elicit and discuss what determines *which* facts are represented and shapes *how* they are represented. Through these determinants, we also seek to document how modelling practices have changed over time, why understanding these changes is important, and to discuss how they may evolve in the future. In a first section, we show that the representation of facts in

FSM is dependent on features of the target, the forest sector, in particular its boundaries, the nature of the facts it comprises, and the roles played by empirical data and theory. In a second section, we argue that models are shaped by the historical context of their development. We recount how different methodologies were developed since the 1970s, with different goals, and highlight how research up to today has been conditioned by these early developments. In the third section, we focus on how the applied uses of FSM for decision support influences modelling practices. We highlight that facts are incorporated into scenarios used to perform simulations, forming narratives used for a dual purpose: provide support for decision-making and get a better understanding of model behaviour. Building on previous sections, we finally discuss why understanding these determinants is important for modellers, and how practices may evolve in the future.

1. The Representation of Facts in Forest Sector Models Depends on the Features of their Target, the Forest Sector

1.1. The Forest Sector: A Complex Target with Unclear Boundaries

The term "target system" is often used to refer to what models represent (Gräbner, 2018). In economics, models as representations range from idealizations where some properties are isolated and simplified to constructions that seek to mimic their target more precisely. However, some see models as "fictions" constructed from theory as analogues to their target without being built *from* it (Morgan and Knuuttila, 2012). In any case, if understanding is to be gained about real economies, models and targets need to "resemble one another in suitable respects and sufficient degrees" (Mäki, cited in Morgan and Knuuttila, 2012, 70). Therefore, what is found in a model is likely to be influenced by what it surrogates for. In the following paragraphs, we argue that facts representation in FSM is largely shaped by the characteristics of their target system: the forest sector.

As outlined in the introduction, the forest sector is often thought of as comprising several integrated activities. For Solberg, the forest sector is composed of "both forestry and forest industries and the interactions between these two activities" (Solberg, 1986, 420). Similarly, Buongiorno defines it as consisting of "all the activities related to the growing and harvesting of wood in forests, to the transportation and transformation of this wood in forest industries and to the utilization of the resulting products in downstream activities" (Buongiorno, 2014, 291). This segmentation of the target into an upstream segment (forestry) and a downstream segment (industries) is common. It implies that the target is large and complex, due to comprising structures and processes integrated both horizontally and vertically (Johnston and van Kooten, 2014), but also of different natures: biological dynamics, economic behaviours, industrial processes, etc.

Consequently, FSM are rather complex and large models (compared to idealised models), and represent natural, technological and economic facts, and their interactions. The word "bio-economic" is sometimes found to describe them (Caurla, 2014), and they can be thought of as belonging to the larger family of "integrated models," in the sense that their target crosses boundaries between several sub-components while model building crosses the boundaries between several disciplines (Hamilton et al., 2015). However, due to the large size and complexity of the forest sector, not all FSM share the same exact target. Some models focus on the industry side rather than on the forestry side (and vice-versa), or on specific sub-segments of the forest sector (e.g., bioenergy production). Such foci broadly correlate with local features of the forest sector. Scandinavian countries possess large, competitive and integrated forest industries: models developed with this scope offer detailed descriptions of industrial processes and biomass procurement (Bolkesjø, Trømborg, and Solberg, 2006; Trømborg, Bolkesjø, and Solberg, 2013; Mustapha, Trømborg, and Bolkesjø, 2017). On the other hand, the French forest sector is characterised by a high degree of heterogeneity in environmental conditions and an industry that is less integrated: model development there focuses on representing diversity in forests and forestry practices (Lobianco et al., 2015; Lobianco, Delacote et al., 2016).

The forest sector is not isolated and is linked to the rest the economy. Timber is an important material for construction, woody biomass is a significant feedstock for the production of energy and forestry has complex land-use interactions with agriculture and urban development. However, the forest sector is usually considered small enough in any given territory for it not to influence the general economy. As a result, FSM are usually partial equilibrium models, and links to the general economy are taken into account through exogenous variables. Links to other individual sectors are represented similarly, with the exception of multi-sector models (e.g. Adams et al., 1996; Eriksson, 2015) or model couplings (e.g. Caurla et al., 2018), where links are made explicit by using several models together.

1.2. Representations, Theory and Empirical Data

In FSM, different methods are employed to represent facts of different natures, and we want to emphasize the varying role played by theories and empirical data. Natural dynamics in FSM are often represented in "forest inventory projection models" (Wear and Coulston, 2019). These take the form of transition matrices where volumes of wood or forest areas are measured in biophysical units and categorized into several compartments (e.g. tree size, tree species, ownership categories), while rules describe fluxes between these compartments (e.g. yearly tree growth). These categories and metrics correspond to those used by real world forest managers, and empirical data from actual forest inventories is used to calibrate models and make them "fit" to reality: the representation of natural facts is constructed to mimic reality. Similarly, technological processes are usually represented as input-output processes, calibrated from real-world plant-level or aggregated industrial data (Northway, Bull, and Nelson, 2013).

Modelling of economic facts relies more heavily on theory as a basis to construct a stylized analogue to the real world. Production and consumption behaviours are often represented with supply and demand functions whose shape derives from economic theory and intuition. As explained by Buongiorno et al., timber supply theory and derived demand theory for raw material inputs are at the origin of market representations in the Global Forest Products Model (GFPM, Buongiorno et al, 2003, 61). At the sectoral level, trade must be factored in: many FSM rely on spatial price equilibrium (Samuelson, 1952) and the law of one price, assuming that price differences across regions are only due to transaction costs. Other FSM call on the optimal harvesting framework (Faustmann, 1849) to represent timber supply behaviours (e.g. Lobianco et al., 2016b; Pohjola et al., 2018). While theory provides the building block for representing economic facts, empirical data also has a role to play. Similarly to natural facts, model calibration uses databases such as FAOSTAT, and the quality of these databases may influence the quality of representations (Kallio et al., 2018). When basic calibration fails to fully explain observed patterns, methods such as positive mathematical programming may also be used (Johnston and van Kooten, 2017). Empirical data also plays a role in estimating model parameters, in particular demand and supply elasticities, which originate from econometric studies based on statistical theory (Rougieux and Damette, 2018; Sauquet et al., 2011). Econometrics then feed FSM, or, seen from the other side, "forest sector models are tools that can translate the behavioural information of econometric studies" (Toppinen and Kuuluvainen, 2010, 6). Empirical data can also be used to validate FSM and assess the accuracy of simulation results against observed data for a past period.

Then, what type of models are FSM? Economists often establish a broad distinction between mathematical models, based on economic theory, and econometric models, which also incorporate elements of statistical theory (Morgan and Knuuttila, 2012). Even though econometrics play a role in representing the forest sector, FSM are to our opinion more akin to the former. FSM can also be considered computational models in the sense that they are composed of sets of procedures and rules, in particular regarding natural and technological facts, but also because they are used for simulation, "grow their results from the initial conditions," and sometimes do not allow for analytical proof (Gräbner, 2018, 5). FSM incorporate elements of positivity, i.e.

representing what is, in their bottom-up, technical representation of many processes. This, as we will see in subsequent sections, partly relates to their development as applied tools for forest policy planning. However, this is often limited to processes that are well defined or central to the question studied (Buongiorno, 1996). For other facts, such as spatial equilibria or consumption behaviours, technical representations are harder to construct, either because there is a lack of data or a lack of understanding of the process. In these cases, theory-based optimisation algorithms or stylized equations may be used: because of this, FSM also incorporate normative elements, i.e. representing what ought to be.

1.3. Spatial and Temporal Dimensions in Representing the Forest Sector

The forest sector's relationship to space and time significantly influences how facts are represented in models. The forest sector is a marker of space from socio-economic, physical and cultural perspectives. Forests constitute a major land use in many parts of the world and structure landscapes, harbour resources and provide many amenity benefits (Brockerhoff et al., 2017). Through these, they enable economic activity and the subsistence of local communities (e.g. Eurostat, 2019; Wiersum et al., 2018; Nambiar, 2019), while also contributing to a "sense of place" (Stedman, 2003; Gunderson and Watson, 2007). At the same time, the timber industry is globalised, wood products are traded throughout the world (Vlosky, 2014; Li, Mei, and Linhares-Juvenal, 2019), and forests enter international policy discussions due to their importance regarding environmental challenges (Smith, Molina Murillo, and Anderson, 2013; Haug and Gupta, 2013). However, forest policy is in many instances decided at the national level, and some countries undergo a gradual shift towards decentralised governance (Sergent, 2017; Sergent, Arts, and Edwards, 2018). The forest sector hence stands at a crossroads between global, national and local scales (Sergent, 2010; Woods, 2013; Lenglet, 2018). Consequently, FSM are spatialized models. Because the law of one price puts a focus on transaction costs, and because the forest sector is transport intensive, space is prominently represented through distances between places and associated transport costs. These concern both natural and economic facts, e.g. distances from harvesting areas to sawmills, distances from sawmills to second transformation industries. Most models use several *regions* as places. These can be administrative units such as EU member states (Schneider et al., 2008), or forestry-related entities (e.g. Finnish forestry centres in Kallio et al., 2008). Usually, exact locations are unknown and several units are represented together at a fictional "medium" point: distances between regions is the primary representation of space. However, some models represent facts more precisely, as if on a map-like structure where locations are given to individual industries or forestry units (e.g. Latta et al., 2018). In addition, due to the forest sector being involved in spatial dynamics at various scales, FSM are often multi-scale models, regardless of their scope. For example, the global GFPM model has several regions trading with one another through a "world" region (Buongiorno et al., 2003), while the model in Lobianco et al. (2015) includes a local scale, a regional scale and a "rest of the world" region.

Furthermore, forest resources are natural resources which, in economics, echo to usual questions of use over time, scarcity and intertemporal ethics. In forestry, decisions are taken over particularly long-time horizons. For example, rotation lengths for oaks reach 120 years in Northern Europe and go beyond 175 years in central Europe (Attocchi, 2015). Owners may not see the outcomes of decisions they take, and forestry-related traditions and the passing of forestland on to next generations have been shown to be important motives for owners (e.g. Hujala et al., 2004; Bengston et al., 2011; Ficko et al., 2019). Time has also been a core issue in forest economics, exemplified in the works of Faustmann (1849) and his predecessors and successors (e.g. Hartman, 1976; Samuelson, 1976), where the "cost of time" and the search for "maximum sustained yield" are core issues (Peyron, 1999). In operational research, these upstream dynamics relate to "strategic planning." On the other hand, downstream dynamics in forest industries operate on shorter time spans, and pertain to "tactical" (months and years) and "operational" (days and hours) planning (D'amours, Rönnqvist, and Weintraub, 2008). This is particularly prevalent in bioenergy production, where the consistency of biomass supply and seasonality are core issues (Shabani, Akhtari, and Sowlati, 2013). As a result, most FSM are dynamic models: they describe the temporal evolution of their target, and are usually separated into two categories (Latta, Sjolie, and Solberg, 2013). Intertemporal models solve all equilibria simultaneously and assume agents to have perfect foresight (e.g. Sohngen et al., 1999; Galik et al., 2015), while recursive models solve equilibria one at a time, assuming agents to have limited foresight (e.g. Kallio et al., 2004; Buongiorno, 2014). Yearly time steps are the norm for the latter, while 5-10 year periods are common for the former. As a result, intertemporal models are better suited to long-term (50-100 years), normative analysis and strategic planning, while recursive models are better suited to shorter term (10-20 years), positive analysis, thus venturing partly into tactical planning. However, such boundaries are often unclear, and hybrids also exist (Lobianco et al., 2016). These frameworks not only represent facts differently: diverging assumptions on agents' behaviours tell different stories, possibly influencing conclusions drawn about the functioning of the target. Sjølie et al. (2011) shows that different types of industries within their model have varying responses to changing assumptions on agent foresight, while Sjølie et al. (2015) argue that, although using both types of models together may remove some uncertainty, model choice needs to be reasoned when designing methodology.

2. The Representation of Facts is Influenced by the Historical Context of Model Development

In this section, we propose a historical account of how FSM developed from work performed at different institutions, and why. Drawing on more recent literature, we show that current models have developed as successors to these precursors and that, consequently, modelling practices are influenced by past developments.

2.1. Spatial Equilibrium Models and Outlook Studies for the Forest Sector

An important institution in developing early FSM was the US Forest Service, in charge of managing National Forests since 1901.[1] Gifford Pinchot, first head of the Forest Service and figure of the conservation movement, was an advocate for scientifically grounded, multiple-use management, highlighting the importance of resource permanence and sustainable yield. Following strong increases in forest use after World War II, the equality of several forest objectives was enshrined in the Multiple-Use Sustained-Yield Act of 1960. The Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974 subsequently required the Forest Service to develop an integrated approach to forest planning based on long-term assessments, including economic considerations (Alston, 1972; Bowes and Krutilla, 1985; Wadsworth and Fedkiw, 2000; Williams, 2005). Assessments performed up to World War II (Hough, 1878; Graves, 1934) had largely relied on expert judgement, while assessments in the 1950-1980 period (US Forest Service, 1973; 1965; 1958) used "gap" models where demand and supply were forecast separately by extrapolating past trends. As stated by Adams and Haynes, these "were estimates of future demand and supply volumes at something other than equilibrium price" and showed their limits when prices became volatile in the 1970s (Adams and Haynes, 2007, 7). The RPA assessment system emphasised the importance of capturing supply-demand-price relationships as well as the regional nature of the sector in periodical assessment reports: research was orientated towards developing spatial price equilibrium (SPE) models. At the same time, a second research cluster developed at the International Institute for Applied Systems Analysis (IIASA), an institution founded in 1972 where research focused on developing global models. In

[1] National forests had been established under the Forest Reserve Act of 1891 after concerns had arisen about private exploitation of common forestland, and their management was shaped by the Organic Act of 1897, often seen as a compromise between conservation and exploitation.

particular, IIASA was involved in developing early Integrated Assessment Models (IAM) of the energy-climate system (Matarasso, 2007). There, the Global Forest Sector project, conceived in the late 1970s and launched in 1980, aimed to "study long-term developments in the production, consumption, and world trade of forest products," and would develop the first global FSM (Kallio et al., 1987, ix).

FSM from that period find part of their origin in the works of Koopmans and Dantzig on transportation systems, activity analysis and linear programming (Koopmans, 1949; 1951; 1953; Dantzig, 1951) and, more generally, in works at the Cowles Commission aiming at the mathematisation of economic problems, which were influential in developing other technical-economic models like IAM (Matarasso, 2007). Following the 1949 Cowles conference on "Activity analysis of production and allocation" (Dantzig et al., 1951), Samuelson (1952) proposed a solution to SPE through resolution of a mathematical programming problem where net social payoff is maximized under a set of constraints. The solution was later refined using methods based on quadratic programming, linear approximations and extended to include activity analysis (Takayama and Judge, 1964a; 1964b; 1970; Duloy and Norton, 1975). As stated earlier, FSM also include econometric equations to represent supply and demand behaviours. Through these, they are related to econometric studies of wood products markets, such as the work of McKillop (1967). Some FSM also find part of their origin in the System Dynamics (SD) framework proposed by Forrester (1969)—used in the Club of Rome report (Meadows et al., 1972)—where emphasis is on change and the system's evolution is described by sets of rules and differential equations. A synthesis was proposed in the PELPS software (Gilless and Buongiorno, 1985), a modelling environment for equilibrium models where static market equilibria are described with econometric equations and activity analysis, solved with mathematical programming, following which a "dynamic phase" akin to SD recursively updates conditions (Buongiorno, 1996).

2.1. Timber Supply Models, Optimal Harvesting and the Economics of Natural Resources

A second approach is found in Supply Models (SM) developed at Resources for the Future (RFF), a research institution which, since the 1950s, focused on resource and environmental economics, particularly dealing with scarcity issues (Pearce, 2002). SM first find their root in the optimal harvesting problem, which is concerned with answering one of the oldest questions in forest economics: "when is it optimal to cut a tree/stand?" Early contributions date back to the 18th century and include thoughts and experiments by De Fenille (1791), Duhamel du Monceau (1764) and Hartig (1805). The solution as we know it today was proposed by Faustmann (1849) in his optimal rotation model where the present value of forest rents from an infinite repetition of forest rotations, or land expectation value, is maximized. Even though his model did not immediately disseminate (Peyron, 1999), it came back to the forefront following Samuelson's (1976) essay reconciling it with modern economics and subsequent extensions to non-timber amenities (Hartman, 1976) and risk (Reed, 1984). SM find their second root in Hotelling's (1931) well known model of the optimal use of non-renewable resources over time. These were adapted to the optimal harvesting of old-growth forests, considered non-renewable resources (Lyon and Sedjo, 1986). Other forest-related concerns at RFF at that time included steady-state forestry, multiple-use forestry and conservation economics (e.g. Hyde, 1980; Bowes and Krutilla, 1985; 1989).

Lyon (1981) and Lyon and Sedjo (1983) developed a synthesis of the "old-growth drawdown" and "steady-state forestry" approaches, which culminated in the creation of the Timber Supply Model, presented among others in Sedjo and Lyon (1990) and Sohngen et al. (1999). It assumes the forest sector to be transitioning from harvesting non-renewable primary forests to harvesting renewable secondary forests. Supplies from multiple regions arise from harvests that follow the Faustmann logic, aggregated to meet an exogenous demand. The model is formulated based on optimal control theory: rules of motion control the system's evolution (e.g. forest growth) from an initial state, and an objective function consisting of consumer surplus net of forestry costs is maximised. The result is an intertemporal and global harvest-scheduling model where a benevolent social planner optimises the use of forest resources over time, explicitly linking timber stocks, supply, harvest levels and forest investments in several regions and over various types of forests.

2.2. FSM Subsequent Development was Driven by Model-Based Policy Expertise

As stated by Solberg in an early contribution, FSM's main purpose is to perform forest policy analysis, i.e. the "analysis of the effects of forest policy means" (Solberg, 1986, 420). From the 1980s onwards, FSM have continued to be developed in close relationship with institutions in charge of or interested in forest policy and planning and, over the years, they have been used as tools for prospective analysis in the forest sector and used to perform outlook studies (Hurmekoski and Hetemäki, 2013). The development of FSM thus replaces itself within a more general trend of using mathematical simulation models for policy planning. As recounted by Maas, mathematical "structural models" based on econometrics and developed at the Cowles commission had been dismissed in the 1950s because of the low accuracy of their predictions (Maas, 2014, 76-98). Model simulations came back to the forefront of economics in the 1970s, when the utility of structural models was recognised not to be in predicting, but rather in their capacity to forecast and explore possible courses of action. They were in particular developed by the Central Planning Bureau and later the Central Bank of the Netherlands as part of their planning process, and contributed to "the reinforcement of the bank's position in policy preparation" (ibid., 150-156). As a result, FSM are related to many other types of 'structural' models developed since that time for various sectors, which seek to capture the "underlying structure" and "causal connections" within economies (ibid., 81).

Work at the US Forest Service yielded models of North-American solid wood products and pulp and paper markets used for all RPA assessments up to 2005 (Adams and Haynes, 2007). With similar methods, the global GFPM model was developed and in the FAO's 1999 global forest products outlook study (Zhu, Buongiorno, and Tomberlin, 1998; Tomberlin, Buongiorno, and Zhu, 1999). In an effort to anchor national RPA assessments within an international context, a national-level derivative was created and used in post-2005 RPA assessments (Ince et al., 2011). The Forest Service was also involved alongside several universities in developing FASOM, a model of the US forest and agricultural sectors, which draws on both strands of early FSM (Adams et al., 1996).[2] It was used to assess climate and energy policy (Beach and McCarl, 2010), and adapted for Europe (Schneider et al., 2008) and the pacific north-west (Adams and Latta, 2005).

In Europe, IIASA's Global Forest Sector project yielded the global SPE model GTM (Kallio, Dykstra, and Binkley, 1987), but also a model based exclusively on SD (Lönnstedt, 1983). Drawing on this work, models were developed to assess national-level policies, first at IIASA, but later also at the European Forest Institute and several European universities. These include SPE models for Austria (Schwarzbauer, 1990), Finland (Ronnila, 1995), Norway (Trømborg and Solberg, 1995) and the European Union (Kallio, Moiseyev, and Solberg, 2004), and SD models for Austria (Schwarzbauer, 1990), Sweden (Lonnstedt, 1986) and Eastern France (Lönnstedt and Peyron, 1989). European outlook studies have been performed since 1952 by the FAO/UNECE. They mostly rely on econometric models (e.g. Baudin, 1995; Kangas and Baudin, 2003; Jonsson, 2012), but have recently turned to using FSM as well. The sixth outlook study, EFSOS (FAO, 2005), used EFISCEN,[3] and the seventh, EFSOS II (FAO, 2010), a model developed by the European Forest Institute.

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[2] Samuelson's SPE framework had also been used for models of the agricultural sector from the 1970s, both in the US and at IIASA (Baumes, 1978; McCarl and Spreen, 1980; Norton and Schiefer, 1980).

[3] EFISCEN focuses on natural dynamics in forests and on timber harvests, but demand is exogenous and timber industries are not represented. Hence, it can be considered a large-scale forest simulator rather than forest sector model in a strict sense.

2.3. *Current Research is Still Shaped by Early Developments*

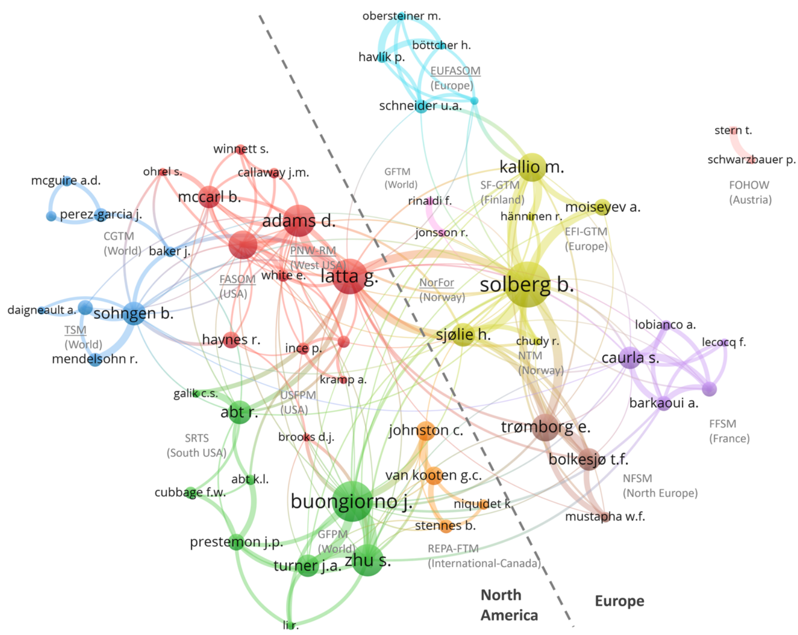
As outlined above, models developed in the 1990-2010 period have largely relied on previous efforts. Since reviews by Caurla (2013) and Latta et al. (2013), this trend in model filiation has continued. Most models cited above are still used in updated forms (e.g. Beach and McCarl, 2010; Galik et al., 2015; Buongiorno and Zhu, 2017; Favero et al., 2018; Kallio et al., 2016; 2018; Kallio and Solberg, 2018), with the exception of SD models, rarer today (Schwarzbauer et al., 2013; Stern et al., 2015). New SPE models include the Scandinavian NFSM (Mustapha, 2016), the global RPFTM (Johnston and van Kooten, 2016; Sun and Bogdanski, 2017) and GFTM models (Jonsson et al., 2016), while STIMM is a Swedish timber supply optimisation model (Gong, Löfgren, and Rosvall, 2013; Guo and Gong, 2017), and several regional models were developed for Canadian provinces (Niquidet and Friesen, 2014; Peter and Niquidet, 2016). Other recent models are not directly sourced from their older counterparts, but still show resemblances. The French FFSM (Caurla et al., 2010) was developed using a IIASA-inspired recursive framework, but includes a detailed description of forest resources as found in SM models. This indirect filiation was reinforced in the later FFSM++ model (Lobianco, Delacote et al., 2016), where forest investment was made endogenous by adding an optimal harvest scheduling module based on Faustmann (1849). Another recent model is LURA for the USA (Latta, Baker, and Ohrel, 2018). Like SPE models, it is recursive, uses mathematical programming to solve static optimisation problems, and the objective function includes transport costs. However, it has a detailed description of forest resources and focuses on optimally allocating supply from various locations to meet an exogenous domestic demand, drawing a parallel to SM models.

These cross-influences in model development have benefited from FSM developing within a small research field. For example, the Global Forest Sector project at IIASA was partly financed by the US Forest Service and the FAO, and included visits by scholars involved in the development of other models for the RPA assessment system or at RFF (e.g. J. Buongiorno, K. Gilles, K. Lyon, R. Sedjo).[4] More recently, the Norwegian NorFor model was developed by researchers involved with a recursive model derived from work at IIASA on the one hand, and others participating in building intertemporal models in the US on the other hand. As a result, NorFor integrates aspects of both approaches (Sjølie et al., 2015). This structuration of the research field along historical teams can be witnessed in Figure 1, where clusters

[4] See acknowledgements, introduction and preface in Kallio et al. (1987). Several of these scholars also co-authored chapters in the book. Similarly, scholars from the Cowles commission influential in developing IAMs such as Dantzig, Koopmans and later Nordhaus have also been involved at IIASA (Matarasso, 2007).

generally correspond to either one model or to several models with strong historical ties. Across clusters, scholars involved in models sharing historical ties display higher levels of relatedness, for example G. Latta and H. Sjølie, or B. Solberg, E. Trømborg and T. F. Bolkesjø. The same is true of scholars having developed models with similar approaches. The other major divide is between scholars belonging to research teams based in North-America, and those located in Europe. As we discuss in section 4, the fact that FSM have an applied use in decision support conditions a large part of modelling activities. Hence, it is not surprising that the bibliographic coupling metric highlights the geographical clustering of the field, even when models do not belong to the same historical "family" (e.g. EUFASOM and EFI-GTM). In such instances, relatedness is due to proximity in policy-relevance.

Figure 1: Bibliographic Network of Scholars in the FSM Field, Based on Bibliographic Coupling



Source: Data was retrieved from Scopus database in July 2019 following the methodology used in Riviere et al. (2020). A bibliographic-coupling link is formed when two publications share common references. The size of items is proportional to the number of papers each scholar has authored, distances between items indicates their level of relatedness, and colours correspond to clusters based on item relatedness. Model names have been added manually based on authors' knowledge. Models whose names are underlined are intertemporal optimisation models, others are recursive models. For visibility purposes, only scholars with at least 3 papers are shown. The network was generated using VosViewer (van Eck and Waltman, 2010) software.

3. Facts Representation in FSM is Conditioned by their Applied Purpose for Decision Support

In this section, we argue that FSM constitute a classical example of how economists interact with models: they "ask questions, use the resources of the model to demonstrate something, and tell stories in the process" (Morgan, 2012, 218). At the same time, their applied purpose for decision-support sets them apart from more theoretical, idealised models and strongly influences modelling practices.

3.1. Model Building and the "External Dynamics" are Heavily Influenced by Policy Debates

Morgan presents the first step of model reasoning in economics as to "create or construct a model relevant for a topic or problem of interest," the underlying assumption being that the problem predates the model (Morgan, 2012, 225). The same discourse is found in the FSM literature: following Solberg, forest policy analysis has meaning only if clear political objectives are defined, and "models should be related to solve problems, not the opposite that the model chooses the problem to be analysed" (Solberg, 1986, 423). Consequently, while the need for policy planning has triggered the creation of FSM, it is the content of policies that shapes modelling practices. Once created, models need to be "questioned to make use of their resources" (the "external dynamics" in Morgan, 2012). Due to the applied nature of FSM, the origin of questions is easily identified: they concern policy-relevant issues, and are asked following requests from institutions or more distant impulsions from policy debates. To a large extent, questions concern the real world and take the form of assessments of a shock's implications for the forest sector. For instance, Caurla et al. (2013) and Moiseyev et al. (2014) assess the consequences of sector-wide carbon taxes. Such examples have a predominantly positive analysis dimension, where the focus is on assessing the model world's response to the shock in order to improve policy design and planning. However, some other questions have a stronger normative dimension, where models are used to highlight the optimal path to reaching a certain situation, forming an image of the future that can guide policymaking. For example, Favero et al. (2017) explore optimal combinations of forest-based mitigation practices to reach climate targets. FSM can also be, even though it comes up more rarely, used to answer questions about the "world in the model." For example, Sjølie et al. (2011) investigate how their model responds to different assumptions on agent anticipations, and results tell more about how the model behaves than about the real world.

There are several ways in which policy debates influence modelling practices. First, models are developed with a geographical scope specific of the issue they address. Investigating trade policy usually requires an international model (e.g. van Kooten and Johnston, 2014;

Buongiorno et al., 2017), while non-trade forest policy is usually assessed with national models, owing to the fact that forestry is commonly regulated these levels (e.g. Kallio et al., 2008; Caurla et al., 2013). An exception is found in energy policy, partly regulated at the EU and US state levels, which shows in model use (e.g. Moiseyev et al., 2011; Galik et al., 2015). Regional models can capture fine-scale patterns in resource use and transportation, and enable the investigation of biomass procurement or landscapes issues (e.g. Niquidet and Friesen, 2014; Costanza et al., 2017). Besides, models are developed to deal with what is locally relevant. For example, models developed in Canada have extensively addressed the US-Canadian lumber dispute (e.g. Devadoss et al., 2005; van Kooten and Johnston, 2014; Johnston and Parajuli, 2017), while several papers from Europe evoke relations between the EU and its trade partners, such as Russia or developing countries (e.g. Moiseyev et al., 2010; Solberg et al., 2010; Lauri et al., 2013). Similarly, the EU being a large importer of bioenergy, FSM from exporting regions have contributed to assessing local consequences of EU demand (e.g. Rafal et al., 2013; Galik and Abt, 2016).

Second, as policy agendas shift over time, so do models. Starting in the 1990s, environmental and climate issues have become more prevalent in FSM research (Riviere, Caurla, and Delacote, 2020). This parallels advancements in scientific knowledge on climate change (IPCC, 1990; 1996) and the emergence of policy platforms such as the United Nation Convention on Climate Change and the Kyoto protocol (Gupta, 2010; Böhringer, 2014). In the last decade, bioenergy production has been the major focus, echoing the establishment of modern energy policy, such as the EU energy directives of 2001, 2009, and the "20-20-20" energy goals (Solorio et al., 2017). A good and recent example of this interconnection with policymaking is found in Kallio et al. (2018), where authors investigate the economic implications of setting "forest reference levels" in each EU member state. The paper was submitted in December 2017 and published in July 2018, but the actual legislation came out in April 2018 (European Parliament and European Council, 2018) and reference levels would only be proposed by countries a year later. The paper hence refers to preliminary documents (European Commission, 2016; 2017) and authors also mobilise their own knowledge of the process. Shifts in policy debates have led FSM to incorporate new facts to answer new questions. Couplings with circulation models have enabled incorporating the natural dynamics of climate change (e.g. Perez-Garcia et al., 1997), and couplings with IAM the inclusion of mitigation strategies (e.g. Tavoni et al., 2007). New technologies have been added as input-output processes to represent bioenergy production (e.g. Folsland Bolkesjø et al., 2006) and carbon accounting modules have been developed to account for carbon sequestration (e.g. Lobianco et al., 2016a; Wear and Coulston, 2019).

3.2. Facts are Incorporated into Narratives Forming the Base for Scenario Analysis and Simulations

The next step of model reasoning is to mobilise the model's resources to demonstrate an answer to the question (the "internal dynamics" in Morgan, 2012). Forest sector modellers have at their disposal a large mathematical system where parameters can be added, their values changed, and model behaviour can be altered by changing computing rules. To mobilise these resources, forest sector modellers rely on *scenarios*, i.e. "coherent and plausible stories, told in words and numbers" (Swart et al., 2004, 139), and on *scenario analysis*, i.e. the exploration of scenarios with models. Scenarios are often sourced from mixed qualitative-quantitative narratives, but need to be translated into the quantitative mathematical and programming language of the model (Hurmekoski and Sjølie, 2018). In this process, because only a finite and limited amount of parameters can be used, scenarios are often simplified and reduced to their core components and messages. To be useful for decision-support, they must also incorporate facts that are both plausible and feasible. As a result, they are often based policy orientation documents or technical reports. For example, Lecocq et al. (2011) refer to contemporary discussions on a carbon tax and government-ordered reports for scenario-building (Quinet, Baumstark, and Célestin-Urbain, 2009). Due to their large size, complexity and to expertise generally requiring quantified outputs, FSM "demonstrations" take the form of numerical simulations. Several scenarios means running several simulations and analysing their results, often compared to a "business as usual" scenario: forest sector modellers interact with their models in a way that is not too distant from that through which forest ecologists interact with their field experiments.

This process can be described as creating "what-if" stories with simulations, a rhetoric found in FSM research (Hurmekoski and Hetemäki, 2013), but also more widely in economic modelling (Maas, 2014, 151). Scenario-thinking has for example been documented in the construction of storylines used in the case of climate and energy issues investigated with IAM (Fortes et al., 2015). More generally, scenario analysis has been used to deal with sustainability questions involving human-environment interactions, with or without models, and is characteristic of prospective problems involving complex systems and long-term dynamics (Swart, Raskin, and Robinson, 2004; Armatte, 2007; Rounsevell and Metzger, 2010). Regarding economics in general, scenario analysis has been a classical procedure for supporting policy planning with simulation models. For example, early simulations for monetary policy in the Netherlands used models "to simulate different trajectories of the economy based on different assumptions about policy measures or international developments," which is the same aim pursued by FSM, albeit in a different domain (Maas, 2014, 158).

The experimental interaction with models is also standard, and falls within what Morgan calls "experiments in the world of the model"[5] (Morgan, 2012, 258-271). However, simulations provide information beyond numerical results: they enable assessing the transmission of economic signals throughout the forest sector, isolating and highlighting the determinants of a mechanism in that complex system, and assessing the sensitivity of a mechanism to its determinants. To do so, forest sector modellers run several simulations where parameter values vary and, more recently, some have turned to sensitivity analysis methods such as Monte-Carlo simulations (e.g. Kallio, 2010; Buongiorno and Johnston, 2018). In doing so, they add variability to the experiment, which is necessary because FSM are largely deterministic models, and perform the necessary "active collusion" described by Morgan.[6] FSM simulations then constitute an "instrument of observation of the world in the model" (Morgan, 2012, 331) by revealing hidden structures and enabling their investigation under impulsions from the user. Morgan's analysis then corroborates Solberg's early intuition of FSM as exploration tools for scientific enquiry, illustrated in his writing that FSM helps scientists understand "what are the most essential relations to explore more in detail empirically and theoretically" (Solberg, 1986, 425).

4. Concluding Remarks: Going Forward with Forest Sector Models

In previous sections, we have highlighted several categories of determinants which we believe have a strong influence on the representation of the forest sector in FSM. These relate to the target, its boundaries and features, but we also showed that modelling practices are influenced by past research and the policy context of model development.

Even though the activity of model developers may be partly oriented by policy debates, choosing and building models remains a critical step on which researchers have agency, and knowledge of the determinants behind modelling practices can only benefit the research community. FSM have known 50 years of continued development and successive improvements through an iterative process. Many methods have been inherited from past efforts, and exchanges across research teams have happened on several occasions. As we have seen, the context of model development, local specificities as well as methods and data available at the time can all be important determinants in shaping

[5] As opposed to models used in laboratory experiments, which is another type of modelling in economics.

[6] In addition, this "active collution" sets FSM apart from the econometric models on which they are partly based and where modelers must rely on "Nature's cooperation in creating variability."

models. For these reasons, modellers involved in new research should be encouraged to research the history of their field in order to better understand the whys and wherefores of modelling practices, to adopt the best approaches and to adapt or improve them when necessary. On the other hand, modellers should also be encouraged to disclose and explain the reasons that have led to their modelling choices, and to discuss the constraints they have faced. Current publishing formats may not always enable it, and technical documents can be published in such cases.

A good understanding of such information enables the choice of appropriate modelling methods. As we have seen, several modelling paradigms exist, each with different underlying assumptions. Models based on intertemporal or static-recursive optimisation may not only yield different results, but also behave differently to similar stimuli (Sohngen and Sedjo, 1998; Sjølie et al., 2015). Even within one modelling framework, changing assumptions on agent behaviours has a similar potential to alter results for a given scenario (Sjølie et al., 2011; Lobianco, Delacote et al., 2016). The sensitivity of model results to assumptions regarding the target's functioning not only concerns economic behaviours, but also natural dynamics such as forest growth and carbon sequestration, where bias can be introduced depending on the methods chosen for representation (Wear and Coulston, 2019). In addition, research also depends on the availability and quality of the empirical data used to calibrate models (Buongiorno and Johnston, 2018; Kallio et al., 2018). In all these cases, different results may tell different stories, potentially affecting decision-making, especially when expertise is explicitly required, and it is important for modellers to be aware of such implications when choosing how to model facts. Besides, one should also keep in mind the limitations of these choices when interpreting results and moving from science to expertise, which is often the case with FSM.

Even though our discussion may not be exhaustive, the determinants we have highlighted may also help us get some insight regarding how representations may change in the future. While early applications were mostly dedicated to timber markets, trade, and the availability of forest resources, today, a large part of FSM-derived expertise focuses on wider issues such as climate change mitigation (e.g. Roux et al., 2017) and energy production (e.g. Wiesenthal et al., 2006; Beach and McCarl, 2010). Given their strong ties with policy, we expect FSM to accompany the evolution of policy discussions towards such wider sustainability questions, which raises several questions.

First, dealing with such issues requires the incorporation of new facts into models, including some that go beyond the classical boundaries of the forest sector. While it is possible to extend the scope of FSM to some extent, recent developments seem to favour model integration, a trend which we expect to continue. The use of model couplings, which we have already highlighted, is a way to increase the boundaries of the system represented, and the forest sector has also been introduced in multi-sector models or IAM such as GLOBIOM (Lauri et al., 2019) and FOR-DICE (Eriksson, 2015). Such approaches also present an advantage in enabling the representation of feedbacks between several sectors, which standalone sectoral models, however refined, may not be able to capture.

Second, the investigation of wider sustainability issues raises concerns about the representation of change. Long-term, stringent objectives towards decarbonisation may require deep structural changes, as well as the emergence of new technologies or behaviours (Bataille et al., 2016). In areas of environmental economics focusing on such issues, qualitative approaches have been used to develop "rich qualitative storylines" together with model projections since the 1980s, yielding for instance the IPCC SRES and SSP scenarios (Rounsevell and Metzger, 2010). Outlook studies for the forest sector have largely relied on quantitative models, either FSM or econometric models, both of which exhibit limited ability to capture such changes (Hurmekoski and Hetemäki, 2013; Hetemäki and Hurmekoski, 2016). Some recent steps have been made in FSM research to bridge the gap between quantitative modelling and qualitative approaches. These can reside in the establishment of wider storylines to be used for scenario-building. Kallio et al. (2016) develop scenarios for the Finnish forest sector based on national low-carbon storylines representing "at least four distinctive outlooks for the future" and, more recently, Daigneault et al. (2019) develop "Forest Sector Pathways" from the IPCC SSP scenarios, noting that the FSM community lacks such "stylized scenario inputs and policy assumptions to consistently inform different modelling efforts." Alternatively, new approaches can be based on combining quantitative modelling to qualitative methods to construct scenarios. Hurmekoski and Sjølie (2018) and Sjølie et al. (2016) use methods from the foresight literature alongside FSM, in particular backcasting, a method relying on identifying desirable future states, which can also incorporate stakeholder input. Finally, new modelling paradigms can develop, representing facts differently. Hurmekoski and Hetemäki (2013) propose Agent-Based Models, a method where macro-level trends arise from micro-level, rule-based individual behaviours, as an alternative to the usual partial equilibrium FSM, and Lobianco et al. (2016b) combine a classical market model to an individual-level forest management model in the spirit of an agent-based model.

After 50 years of continued development, FSM may have reached a certain level of maturity in representing the forest sector, changing model scope, developing methods and designing scenarios to answer an ever-growing range of questions. Reaching such a situation enables novel improvements, such as those we just highlighted, to happen not only inside models, but also around them, expanding the perimeter of analyses performed. This, in turn, should allow forest sector modellers to increasingly contribute to exploring sustainability pathways needed to address current environmental challenges, many of which require forestry to play a part.

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