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1 Evolving integrated models from narrower economic tools: the example of forest sector models

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11 Abstract

12 Integrated simulation models are commonly used to provide insight on the complex functioning of social-
13 ecological systems, often drawing on earlier tools with a narrower focus. Forest sector models (FSM) encompass
14 a set of simulation models originally developed to forecast economic developments in timber markets, but now
15 commonly used to analyse climate and environmental policy. In this paper, we document and investigate this
16 evolution through the prism of the inclusion of several non-timber objectives into FSM. We perform a systematic,
17 quantitative survey of the literature followed by a more in-depth narrative review. Results show that a majority of
18 papers in FSM research today focuses on non-timber objectives related to climate change mitigation, namely
19 carbon sequestration and bioenergy production. Habitat conservation, deforestation and the mitigation of
20 disturbances are secondary foci, while aspects such as forest recreation and regulation services are absent. Non-
21 timber objectives closest to the original targets of FSM, as well as those for which economic values are easier to
22 estimate, have been more deeply integrated to the models, entering the objective function as decision variables.
23 Others objectives are usually modelled as constraints and only considered through their negative economic impacts
24 on the forest sector. Current limits to a deeper inclusion of non-timber objectives include the models' ability to
25 represent local environmental conditions as well as the formulation of the optimisation problem as a maximisation
26 of economic welfare. Recent research has turned towards the use of model couplings and the development of
27 models at the local scale to overcome these limitations. Challenges for future research comprise extensions to other
28 non-timber objectives, especially cultural services, as well as model calibration at lower spatial scales.

29 **Keywords:** forest sector model, forestry, economics, environmental modelling, ecosystem services, integrated
30 assessment

31 **JEL codes:** C61, L7, Q21, Q23, Q57

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38 1. Introduction

39 Human societies are today facing a wide array of complex environmental, social and economic challenges at the
40 global scale, including but not restricted to, climatic changes, the erosion of biodiversity and transitioning to low-
41 carbon economies [1-3]. Addressing these challenges requires developing a comprehensive but thorough
42 understanding of intricate social-ecological systems in order to perform so-called *integrated assessments*. These
43 in turn often rely on *integrated models*, which must be able to incorporate ecological, biophysical, economic and
44 social information and dynamics of the systems of interest [4-6]. Yet many such models were initially developed
45 with a narrower focus, requiring changes to be made in order to expand the range of analyses possible. Such
46 developments in turn raise questions concerning the suitability of models.

47 Among social-ecological systems, forests and forestry play a key role in addressing the above-mentioned issues.
48 Forests cover around 30% of land area globally and provide many market and non-market ecosystem goods and
49 services [7-8]. Traditional forest objectives include the production of timber for construction or furniture as well
50 as the manufacturing of paper, which support large industrial sectors. Forestry contributes to climate change
51 mitigation through carbon sequestration [9] and energy or material substitution [10-11]. Forests provide regulation
52 services such as erosion control, water purification, flood regulation and pollination, etc. [12-13], as well as cultural
53 services such as recreation and hunting [14-15]. In addition, forests host a large share of the world's biodiversity
54 and harbour key habitats [16]. These many goods and services are characterised by complex antagonistic or
55 synergistic relationships at different spatial and temporal scales [7, 17], and while forest management often pursues
56 timber production as its main objective, it also affects the provision of other goods and services [18].

57 The relationships between multiple forest management objectives have been studied with various methodologies.
58 Traditional forest economics frameworks such as that of the optimal rotation problem [19] can be extended to
59 account for multiple amenities [20], the joint production of several amenities can be studied by assessing
60 production possibility frontiers [17], and the provision of multiple ecosystem services can be spatially evaluated
61 with mapping tools [21-22]. Several techniques for forest planning have been developed based on group decision
62 making, multi-criteria decision support or public participation [23-25], and forest owners' motives for owning and
63 managing forests can also be analysed using survey methods based on theories in social and behavioural sciences
64 [26]. Among these methodologies, Forest sector models (FSM) encompass a set of simulation tools commonly
65 used for policy analysis in the field of forest economics, with a core focus on forecasting developments in timber
66 production and wood products markets [27-28]. As coupled bio-economic models of timber markets, forest
67 management and biological dynamics, FSM offer a broad overview of forestry and the forest sector, making them
68 good candidates as integrated models able to "*explore the linkages and feedbacks between different system*
69 *components, including the social, economic and ecological implications of different natural or anthropogenic*
70 *factors*" [4].

71 To date, however, there is no detailed, quantitative analysis on how FSM apply to objectives other than the
72 production of timber, in particular environmental objectives. Previous contributions have focused on model theory
73 and development [27-30], or have discussed FSM applications from a broad perspective [28, 31, 32]. The objective
74 of this paper is to fill this gap and investigate how and to what extent forest objectives other than timber production
75 (hereafter, *non-timber objectives*) have been studied using FSM. In particular, we aim at demonstrating how a
76 category of originally narrow models focused on economic analysis has gradually evolved to carry out research
77 on environmental questions, and what challenges this trend towards integration implies. Our objective is twofold:
78 first, we seek to identify which non-timber objectives have been studied in FSM research and to what extent.
79 Second, we want to give an overview of research questions over time, and document and question the evolution
80 of modelling approaches. We rely on the combination of two complimentary methods: a systematic literature
81 review and a more in-depth narrative review. This allows us to provide a quantitative overview of the field as well
82 as to focus on specific aspects through examples.

83 2. Context and review methodology

84 **2.1. Forest Sector Models**

85 FSM are representations of the forest sector based on economic theory. They are mathematical models using sets
 86 of equations and mathematical objects to represent a system, as well as simulation models solved numerically due
 87 to their large size. They were developed in the 1970s as a new way to project developments in timber markets and
 88 have since then been used for policy analysis [27-28, 32]. We present an overview of FSM focusing on four
 89 aspects: the real-world target of FSM, their spatial format, their handling of temporal dynamics, and their objective
 90 function.

91 The real-world target of FSM is the forest sector, which is usually understood as comprising an upstream segment,
 92 forestry, and a downstream segment, forest industries [32]. Forestry encompasses forest resources, their biological
 93 dynamics (e.g., growth, mortality) and timber harvesting, while forest industries encompass the processing and
 94 transportation of wood products and their sale onto the market. The exact boundaries of the forest sector are not
 95 clearly defined, and models do not share the same exact targets. On the forestry side, the least detailed models do
 96 not describe the resource, or only as aggregated timber volumes, while more detailed models distinguish between
 97 several tree species, diameter classes, ownership categories and are spatially-explicit [33-34]. On the industry side,
 98 several market levels can be represented [35]. Most models include several products (e.g., roundwood and
 99 pulpwood), and many include a second level in transformed products (e.g., plywood, lumber.). Generalist models
 100 focus on traditional wood products used for construction, furniture and paper, while specialized models focus on
 101 specific industries such as wood chips [36] or biofuels [37]. FSM vary in their geographical scopes and spatial
 102 formats, and can be developed at the country [38-40], regional [41-42] or global levels [30-43]. Most models are
 103 spatialized and include several demand and supply regions, but a few are aspatial with a single region [44].

104 FSM are equilibrium models where market equilibrium is found by equating supply (quantity of timber produced)
 105 and demand (quantity consumed) for all products. The majority of models finds the so-called spatial price
 106 equilibrium [45] by solving a large mathematical programming problem where the sum of consumer and producer
 107 surpluses net of transport costs, or net social surplus (NSS), is maximised under a set of constraints ensuring non-
 108 negativity of key variables and enforcing lower and upper bounds for some of them [28, 30]. In a case with several
 109 products k and regions (i,j) , NSS is equal for a given year t to:

$$110 \quad NSS_t(D_{ikt}, S_{ikt}, e_{ijkt}) = \sum_i \sum_k \int_0^{D_{ikt}} P_{ikt}(D_{ikt}) dD_{ikt} - \sum_i \sum_k \int_0^{S_{ikt}} P_{ikt}(S_{ikt}) dS_{ikt} - \sum_i \sum_j \sum_k TC(e_{ijkt}), \quad (1)$$

111 where D refers to quantities demanded, S to quantities produced, e to quantities transported between regions and
 112 TC to transport costs (adapted from [30, 46]). The term $\int_0^{D_{ik}} P_{ik}(D_{ik}) dD_{ik}$ corresponds to areas under demand
 113 curves (consumer surplus), the term $\int_0^{S_{ik}} P_{ik}(S_{ik}) dS_{ik}$ to areas under supply curves (producer surplus), and the
 114 term $TC_{ijk}e_{ijk}$ to transport costs.

115 FSM are usually separated into two categories based on their handling of time [47]. Intertemporal models assume
 116 agents have perfect foresight and solve all market equilibria at the same time. These models are well suited for
 117 long-term analyses [28]. On the opposite, recursive models assume limited foresight and solve equilibria one
 118 period at a time. They are made dynamic by recursively updating the model's parameters [30], and are better suited
 119 for short to medium-term analyses. In addition, some models are purely static [48]. In the case of a recursive
 120 model, the optimisation for a given year t can be written as:

$$121 \quad Max_{D_{ikt}, S_{ikt}, e_{ijkt}} NSS_t(D_{ikt}, S_{ikt}, e_{ijkt}), \quad (2)$$

122 with rules on how parameters should be updated after each time period. For example, supply equations in the
 123 French Forest Sector Model [49] (FFSM) are given by:

$$124 \quad S_{ikt} = S_{ikt-1} \left(\frac{P_{ikt}}{P_{ikt-1}} \right)^{\alpha_k} \left(\frac{I_{ikt}}{I_{ikt-1}} \right)^{\beta_k}, \quad (3)$$

125 where S_{ikt} and P_{ikt} are supply and price for the current year respectively and S_{ikt-1} and P_{ikt-1} for the previous
 126 year. Similarly, I_{ikt} is the available forest inventory (timber volume) in year t and I_{ikt-1} the available inventory the

127 previous year. β_k and α_k are the elasticities of supply to inventory and prices respectively. When the model is
 128 intertemporal, all equilibria are solved at the same time and the sum of discounted surpluses is maximised over the
 129 time horizon T using discount rate r :

$$130 \quad \forall t \in [0, T], \text{Max}_{D_{ikt}, S_{ikt}, e_{ijkt}} \sum_{t=0}^T (1+r)^{-t} NSS_t(D_{ikt}, S_{ikt}, e_{ijkt}), \quad (4)$$

131 The determination of quantities produced, consumed, traded and prices is endogenous. Elasticities are usually
 132 estimated econometrically or taken from the literature, and trade data (e.g., from the FAO) and forest inventory
 133 data (e.g., from national forest inventories) are used to calibrate the models. A small number of models do not
 134 follow the general framework described here. For example, the model developed by Schwarzbauer & Rametsteiner
 135 [44] falls within the Systems Dynamics framework, where demand and supply are not determined simultaneously
 136 in an optimisation process, but oscillate around equilibrium values. For more details regarding FSM, the reader
 137 can refer, among others, to [28-30, 50].

138 2.2. Non-timber objectives

139 Forest management can be defined as “the integration of silvicultural practices and business concepts in such a
 140 way as to best achieve a landowner’s objectives” [51]. The main objective pursued by landowners is usually timber
 141 production. This is illustrated by early works on optimal forestry practices such as that of Faustmann [19], where
 142 maximising returns from wood production is the key element. However, forest management can pursue several
 143 objectives in addition to the production of wood [52], and terms such as “multiple-use” or “multifunctional” are
 144 often encountered [52-54]. This multiplicity of potential objectives is recognised in the definition of “sustainable
 145 forest management” [55], and the FAO FRA database [56, 57] uses a classification of forestland according to their
 146 management objectives, illustrating the diversity of objectives that can be pursued (Table 1).

147 **Table 1** Examples of forest management objectives and forest ecosystem services [56-58]

FRA database classification	Krieger (2001)
Production of goods - Industrial roundwood - Fuelwood (bio-energy) - Non-wood forest products	Raw materials (including timber and non-timber products) Food production
Protection of soil and water - Production of clean water - Coastal stabilization - Desertification control - Avalanche control - Erosion and flood protection - Other purposes	Water regulation Water supply Erosion control and sediment retention Soil formation Waste treatment Nutrient cycling
Conservation of biodiversity	Genetic resources
Provision of social services - Public recreation (including hunting and berry-picking) - Carbon sequestration and storage - Spiritual and cultural services	Recreation (including general recreation and hunting-fishing) Cultural services (including heritage values, aesthetics and endangered species habitats) Climate regulation (including carbon sequestration)
Multiple-use (several objectives with none significantly more important than the others)	
Other (than production, protection, conservation, social services and multiple use)	Biological control Disturbance regulation

148 Many objectives relate to the provision of ecosystem services, which can be broadly defined as “the direct and
149 indirect contributions of ecosystems to human wellbeing” [59] and are often categorized as *provisioning services*,
150 *regulation services* or *cultural services* [60]. To give an example, we included in Table 1 forest ecosystem services
151 reviewed by Krieger [58] in their assessment of forest ecosystem values, but some classifications name up to 100
152 services [7]. Not all objectives fall under the scope of ecosystem services. Biodiversity conservation is often cited
153 as a management objective, but biodiversity is usually considered not to be a service, rather a support for services,
154 or even a good [61]. Other objectives are revealed when looking at individual owners’ motivations for owning
155 forests [62-66], and a short review reveals that some would be located further down the ecosystem services cascade
156 and could be considered benefits (e.g., financial stability, passing on to the next generation). Because of the
157 diversity in classifications and definitions, we chose to use the general term “*non-timber objective*” to refer to all
158 finalities pursued by forest owners through forest management other than the production of timber.

159 **2.3. Review methodology**

160 We follow a two-step process, as illustrated in Figure 1. In the first step, we systematically gather scientific
161 publications using Scopus database. A first search query aims at retrieving publications based on historically
162 significant FSM, using the models’ names and abbreviations for them. The list of FSM included in the query is
163 based on publications on the development and history of FSM [27-29, 31]. A second search query uses keywords
164 related to common denominations used to describe FSM, alongside keywords related to the forest sector and
165 economics. This allows us to retrieve publications where other FSM are used. In order to sort articles obtained
166 from the query, and in line with the literature [27-29, 32, 67], we narrow the definition of FSM to models (1)
167 rooted in economic theory, (2) representing the forest sector, i.e., forestry plus forest industries, (3) at the sector
168 scale, and (4) at a temporal scale relevant to forest-related questions (when models are dynamic). Publications
169 where a multi-sector model is used are only considered when the forest sector is the main focus of the paper. These
170 criteria lead us to exclude models at the individual owner or forest stand scale, and biological growth models.

171 **Fig.1** Illustration of the review process: search queries used (left) and analysis of retrieved papers (right).

172 In a second step, we analyse publications in the review dataset. We perform standard bibliometric analyses and we
173 carry out a bibliometric network analysis based on keyword co-occurrence using VOSviewer¹ [68, 69]. Based on
174 titles, abstracts and keywords (and, when necessary, full-texts), we identify papers dealing with non-timber
175 objectives and identify which objectives are being investigated. In addition to this quantitative review, we perform
176 a more in-depth narrative review. We give an overview of research questions (i.e., which aspects of non-timber
177 objectives are being investigated?), review modelling approaches to the inclusion of non-timber objectives and
178 identify current modelling trends.

179 **3. Systematic review and bibliometric analyses**

180 **3.1. Paper count and publishing dynamics**

181 The systematic review yields 248 publications. As shown on Figure 2, the amount of paper published annually has
182 been increasing steadily, and since 2005 at least 9 papers have been published every year. As we conducted the
183 review in July 2019, paper count for 2019 may still increase. We separated papers into two categories: analyses,
184 where a model is used to answer a research question about the forest sector, and non-analyses, which comprise
185 reviews, theoretical contributions and model presentations. We found 51 non-analyses and 197 analyses. Among
186 analyses, 56 (28%) did not consider a non-timber objective, and 141 (72%) did. While the amount of papers
187 considering timber production alone has stayed relatively constant over time, the amount of papers focused on

¹ A co-occurrence link is formed between two keywords when they appear in the same publication. The more often keywords appear together, the stronger the link. Keywords and links are then represented on a network where distances between items indicate their level of relatedness, and items are further separated into clusters. Keywords whose spelling varies across publications are merged using a thesaurus.

188 non-timber objectives has strongly increased in recent years. Since 2010, half or more of papers published every
 189 year have included non-timber objectives.

190 **Fig.2** Distribution of reviewed papers per date of publication and thematic focus

191 As shown in Table 2, a few journals concentrate most papers. The most common are specialised forest economics
 192 journals (e.g., *Forest Policy and Economics*, *Journal of Forest Economics*) and generic forest sciences journals
 193 (e.g., *Forest Science*, *Scandinavian Journal of Forest Research*). Of lesser importance but still well represented
 194 are journals specialised in energy and climate issues (e.g., *Energy Policy*, *Biomass and Bioenergy*, *Climatic
 195 Change*) and resource economics journals (e.g., *Agricultural and Resource Economics Review*, *Environmental and
 196 Resource Economics*). Few papers are published in general economics journal (e.g., 1 and 2 papers in the *American
 197 Economics Review* and *Applied Economics* respectively) or modelling journals (e.g., *Ecological Modelling* and
 198 *Environmental Modelling and Assessments* both have two papers). The Scopus subject areas² most represented are
 199 Agricultural and Biological Sciences (175 papers), Environmental Sciences (166), Social Sciences (74),
 200 Economics, Econometrics and Finance (67) and Energy (34).

201 We propose two possible explanations for these trends: (1) researchers in the field focus their publications on
 202 journals specialised in forestry (with a focus in economics or not) rather than journals that are more generic. This
 203 may be linked to the fact that, historically, forest sector modelling developed within an already specialised field,
 204 that of forest economics [50]; (2) more generic journals may have a low degree of openness to applied, forest-
 205 related topics. Both explanations are a concern, given the wide environmental importance (climate change,
 206 biodiversity) that forests have for society.

207 In addition, we note the relative absence of modelling journals, which could indicate a focus in published papers
 208 on results and policy implications rather than on methods and modelling tools. In the papers we reviewed, those
 209 published in modelling journals were focusing on the development of new “modules” within already established
 210 models [33, 70, 71] or developed new models [72] and contained detailed information about model specifications.
 211 However, the vast majority of papers reviewed contained much less information: given the large size and
 212 complexity of FSM, details about modelling techniques are usually published as separate books or technical reports
 213 [42, 73].

214 **Table 2** Bibliometric information about publishing journals (left) and authors’ country affiliations (right).

Journal	Paper count	Country	Paper count
Forest Policy and Economics	36	United States	131
Journal of Forest Economics	22	Norway	40
Scandinavian Journal of Forest Research	13	Canada	25
Forest Science	12	Finland	24
Canadian Journal of Forest Research	10	France	18
Energy Policy	7	New Zealand	13
Forest Products Journal	7	Sweden	11
Biomass and Bioenergy	6	Austria	10
Canadian Journal of Agricultural Economics	6	Germany	10
Journal of Forestry	5	Italy	7
New Zealand Journal of Forestry Science	5	China	6

² A journal can belong to several categories, e.g., *Forest Policy and Economics* appears in both the Agricultural and Biological Sciences and Economics, Econometrics and Finance categories.

Total

129 (52%)

295^a

215 ^a A paper with several authors affiliated to institutions in different countries is counted several times. As a consequence, total paper count in the right
216 hand side of the table is higher than the total amount of papers reviewed.

217 Most of the research activity seems to take place in developed countries with large forest industries (and hence
218 policy relevance), especially those where the research field originated and where research programmes are likely
219 well established. As shown in table 2, the country most represented in authors' institutional affiliations is by far
220 the United States, which is where a large part of FSM research started [28]. Besides, several models with regional,
221 national and global scopes still in use today are being developed by US-based institutions [39, 73, 74]. European
222 countries such as Sweden, France, Finland, Norway, Germany and Austria are also well represented. These all
223 share the characteristic to have extensive forest areas and/or a large forest industry. Besides, one of the early
224 clusters of model development was based at IIASA, an international research organisation located in Austria [28].
225 New-Zealand and Canada, which also possess significant forest sectors, are also well represented. Countries from
226 other continents are almost absent, in particular countries with tropical forests, despite their environmental and
227 economic relevance. Instead, most issues related to tropical forests (illegal logging mostly) appear in our review
228 to be studied using global models developed in the USA or in Europe, with a focus on international trade [75-77],
229 even when no authors are affiliated to these countries [78]. This point may be explained by the fact that most
230 research related to tropical forests focus on land-use change and deforestation, issues that go beyond the scope of
231 the forest sector alone. This implies that tropical forests are more likely to be treated through land-use change
232 models rather than FSM.

233 3.2. Network analysis and identification of non-timber objective categories

234 We report results from the bibliometric network analysis as a network of keywords in figure 3. Two clusters (A
235 and D) comprise keywords associated with the production of timber and wood products. Cluster A has a stronger
236 focus on forest industries and timber markets, illustrated by keywords such as "trade", "competition", "timber
237 market" or "demand/supply", while cluster D has a stronger focus on forestry, with keywords such as "forest",
238 "forest management" and "timber". Cluster B is associated with the production of renewable energy from woody
239 biomass ("bioenergy", "biomass", "renewable energy/resource", "fossil fuel"), and cluster C is associated with
240 forest carbon and climate change ("climate change", "carbon", "carbon sequestration", "land use change",
241 "greenhouse gas"). Together, clusters B and C refer to the forest sector's contribution to climate change mitigation
242 through energy substitution and carbon sequestration. Keywords referring to methods used, such as "forest sector
243 model", "partial equilibrium model" or "computer simulation" are distributed among all clusters.

244 **Fig.3** Bibliometric network analysis based on keyword co-occurrence (a), and temporal trends in keyword use (b). The size of
245 items is proportional to the number of occurrences, and distances between items indicate their level of relatedness. For visibility
246 purposes, we limited the display to the most common 105 keywords, which corresponds to at least 8 occurrences within the
247 dataset, and only the 500 strongest links are displayed. In figure (a), keywords clusters are represented in different colours,
248 while figure (b) displays the average year keywords were used in.

249 Based on the network analysis and our reading of papers, we identify 5 non-timber objectives in the papers
250 reviewed: bioenergy production (59 papers), management for the regulation of risk associated to disturbances (12),
251 climate change mitigation (45), habitat conservation (22), and water regulation (3). While the latter three
252 correspond to forest management objectives identified in our introductory review, the former two were more
253 delicate to define, and we detail the thought process behind our choice.

- 254 • We chose to consider bioenergy products separately from traditional wood products for three reasons. First,
255 their inclusion in the FSM literature is recent and represents a significant amount of publications where the
256 focus is on technology-intensive products. Second, in forest sciences, fuelwood production is often considered
257 separately from regular timber or paper production. Third, papers often adopt a climate perspective based on
258 energy substitution and avoided emissions, and we consider climate change mitigation to be a non-timber
259 objective. However, we separate "bioenergy" papers from "climate change mitigation" papers because of their
260 specialised and deep focus. The latter have a broader scope, while the former are in-depth analyses of
261 bioenergy industries and their development potential.

- Disturbances such as fires or storms affect the forest’s ability to provide goods and services. In order to mitigate risks associated to these disturbances, managers may take actions they would otherwise no take (e.g., prescribed burning). Besides, disturbances affect both timber and non-timber objectives (e.g., habitats for biodiversity, carbon stored) and, in some cases, only affect non-timber objectives. For example, lowland Mediterranean forests produce little timber, but are heavily managed both at the stand and landscape levels to mitigate fire risks due to threats posed to biodiversity, recreational uses or human settlements [79]. In such a case, fire prevention can even become the main objective. Hence, we chose to consider the regulation of risks associated to disturbances as a separate non-timber objective.

While bioenergy production and climate change mitigation seem to correspond to keywords found in clusters B and C respectively, conservation, despite representing a large number of publications, did not emerge as a consolidated cluster. Instead, keywords such as “biodiversity” and “conservation” appear in cluster A, “deforestation” in cluster C, and other keywords such as “sustainability” or “ecosystem” only appear when adding less common keywords. FSM research on the topic may therefore be less structured or present a wider variety of research questions and keywords. Management for the regulation of disturbances and water services do not appear as consolidated clusters due to the smaller amount of papers. Some clear temporal trends can be identified: the use of keywords in cluster B (bioenergy-related) is more recent, and the use of keywords in cluster D (forestry-related) is more ancient. 90% of bioenergy studies, 60% of climate change mitigation studies and 46% of conservation studies were published after 2010. Climate change mitigation and especially bioenergy production seem to be recent topics, while conservation has been a longer-term, albeit minor focus in the literature. Bioenergy production is the most important non-timber focus in FSM research today, accounting for 37% of publications since 2010.

3.3. How does the inclusion of non-timber objectives affect the models?

The inclusion of a non-timber objective requires the model to be able to quantify, in biophysical or monetary units, the realisation of that objective. If a goal is set for the production of a non-timber good or service (i.e., a certain amount is to be reached), the objective needs to enter decision rules, that is to say, the optimisation problem. Since the objective function in FSM is an economic surplus, only non-timber objectives for which an economic value can be estimated in monetary units can enter the objective function directly. When no monetary value exist, non-timber objectives usually enter the optimisation problem through constraints to the maximisation of net social surplus. Besides, when the level of non-timber objective is to be determined endogenously, a new decision variable needs to be added to the maximisation problem. In cases where the model does not hold the information needed to perform quantification endogenously, a model coupling can be established, where specialised models are used exogenously, and perform calculations from FSM outputs.

We illustrate this with a commonly introduced non-timber objective, *in-situ* carbon sequestration, i.e., in forests. The first step of any inclusion of carbon sequestration into FSM is the quantification of carbon stocks and fluxes. To achieve this goal, many modellers have opted for the development of “carbon accounting modules”, i.e., registries where amounts of carbon stored in several compartments are tracked over time [39, 80-81]. Because carbon quantities are directly linked to forest biomass, these accounting modules rely on forest inventory submodels already present in most FSM and use expansion factors to convert cubic meters of wood to tons of carbon. Wear and Coulston [67] provide a detailed overview of the main assumptions behind forest inventory modules used to project carbon dynamics in FSM. Alternatively, the description of forest resources within some FSM may be too aggregated to allow for a good conversion to carbon contents. In this case, specialised ecological models can be mobilised, as in Kallio et al. [82], where FSM outputs are used as inputs to a forest stand growth simulator where the development of forest biomass and carbon stocks is simulated with more accuracy.

Then, the inclusion of carbon sequestration into FSM can take two routes. Firstly, it can be introduced as an objective through monetisation and subsequent addition to the objective function. A price is given in monetary units per ton of carbon, many estimates being available in the literature [2]. Landowners receive a yearly payment equal in year t to $P_{c,t}(\Delta C_t - \Delta C_t^{BAU})$, where $P_{c,t}$ is the price of carbon in year t , ΔC_t the change in carbon stock

308 between years t and $t-1$, and ΔC_t^{BAU} the stock change in a baseline scenario³. Hence, the sum
 309 $\sum_{t=0}^T (1+r)^{-t} P_{c,t} (\Delta C_t - \Delta C_t^{BAU})$ of payments received by landowners over a period T can be directly added to
 310 NSS in the objective function in equation (4) (e.g., [83-85]). In the case of recursive models, the supply function
 311 is modified to account for the opportunity cost to harvesting due to carbon payments which acts as a tax, e.g.
 312 equation (3) becomes:

$$313 \quad S_{ikt} = S_{ik,t-1} \left(\frac{P_{ikt} - \omega_k P_{c,t}}{P_{ik,t-1} - \omega_k P_{c,t-1}} \right)^{\alpha_k} \left(\frac{I_{ikt}}{I_{ik,t-1}} \right)^{\beta_k}, \quad (5)$$

314 where ω_k is the carbon density of product k , and $\omega_k P_{c,t}$ represents the foregone carbon payment due to timber
 315 being extracted from the forest. Carbon payments themselves need to be added to producer surplus ex-post [86-
 316 87]. In most applications, carbon sequestration is assumed to be an objective pursued on all forestland. However,
 317 in Latta et al. [85], the model endogenously determines land where this objective is to be pursued, and the amount
 318 of land enrolled in the carbon sequestration programme is introduced as a decision variable in equation (4).

319 Secondly, when carbon sequestration objectives are not included in the objective function, they can be introduced
 320 as constraints to the maximisation of net social surplus. In Im et al. [88], this takes the form of a constraint on
 321 carbon fluxes within the forest sector:

$$322 \quad \sum_{t=0}^T (1+r)^{-t} [\Delta C_t^f + \Delta C_t^p] \geq T_{min}^C, \quad (6)$$

323 where ΔC_t^f and ΔC_t^p are changes in carbon stocks in the forest and products pools respectively, discounted by
 324 discount rate r , and T_{min}^C is the carbon flux target over period T . Alternatively, due to the direct relationship between
 325 timber volume and carbon quantities, the constraint can be set as an upper limit to timber harvests [88-90]. In the
 326 next section, these various approaches are reviewed for each category of non-timber objective.

327 **4. Narrative analysis: research questions and the limits to integrating non-timber** 328 **objectives**

329 **4.1. Research questions and transversal issues**

330 FSM were originally developed as market models to perform economic analysis. As illustrated by the high number
 331 of papers focusing on non-timber objectives, they have gradually become tools for environmental assessment as
 332 well. However, many non-timber objectives are only studied insofar as they affect economic activity and timber
 333 production, while others such as bioenergy production are more deeply integrated. We illustrate this fact by giving
 334 an overview of research questions and modelling approaches for each non-timber category.

335 Bioenergy papers largely aim at assessing the potential to develop bioenergy industries, their ability to reach
 336 renewable energy targets and implications for traditional timber industries [76, 91-93]. A strong focus is put on
 337 assessing the effectiveness of economic policy measures such as subsidies to bioenergy production or consumption
 338 [94-96]. Even though the early focus was on bioenergy markets themselves, recent contributions to the topic are
 339 increasingly concerned with the environmental footprint of bioenergy products, and deal with issues such as carbon
 340 neutrality [96-97], carbon stocks and land-use patterns [98-100] and implications for landscapes and habitats [101-
 341 103]. Conversely, several contributions in the conservation category investigate the impacts of bioenergy policy
 342 [104-105]. The integration of bioenergy is the one we believe to be the deepest, owing to the fact that bioenergy
 343 production is easily quantifiable in both physical and monetary units the same way as regular timber products, i.e.,
 344 with a market model assigning prices to quantities produced. In addition, bioenergy products (e.g., pellets,) are
 345 already traded on markets, and data is accessible to calibrate models. Hence, bioenergy production is often
 346 introduced as an endogenous objective in models, and quantities produced are decision variables. In some cases,
 347 energy demand is constrained to account for exogenous renewable energy production targets.

³ In some cases, all carbon sequestered is subsidized, and the ΔC_t^{BAU} term equals 0.

348 Papers on climate change mitigation focus on two broad research questions. First, 13 papers seek to inform general
349 forest policy by evaluating the impacts of climate change on timber markets, industries and forest resources [106-
350 108]. Second, 32 papers investigate the climate mitigation potential of the forest sector and seek to evaluate the
351 costs and effectiveness of mitigation policies and strategies. Most of these papers include quantification of carbon
352 fluxes, and rely on the use of the aforementioned carbon accounting modules, conversion factors or external
353 models to do so. Carbon pricing is a straightforward and established economic method to assign monetary values
354 to carbon stored and avoided emissions [109], allowing for a good integration to FSM. Indeed, 20 papers rely on
355 carbon pricing, either payments for sequestration in forests [86-87, 110], or sector-wide carbon tax-subsidy
356 schemes [111-112]. Carbon prices are usually set by the user, with some exceptions where carbon prices are
357 endogenously determined [113-114]. Other approaches include setting constraints to the optimization in terms of
358 harvest levels [89-90], and more rarely, carbon fluxes [88], eschewing monetization. Some models include the
359 area committed to sequestration as a decision variable [115].

360 Other non-timber objectives are less deeply integrated. Most conservation papers seek to assess tradeoffs between
361 economic activity and habitat conservation, usually quantified in loss of economic surplus or reduced timber
362 supply [40, 104-105, 116-117]. Several papers focus on tradeoffs in deforestation-prone areas [77, 118-119] and
363 three papers assess the economic implications of barriers to the trade of illegal timber [75, 78, 120]. In most cases,
364 conservation does not enter the objective function, is not modelled explicitly and is introduced through constraints
365 to the optimization problem, i.e., land is removed from production, harvest levels or traded quantities are
366 constrained as proxies for conservation practices. Noteworthy exceptions in the sample include Kallio et al. [46]
367 and Schlepner and Schneider [121], where the location of land to be conserved is a decision variable. Similarly,
368 two papers on water services follow a constraint-based approach where forests around streams cannot be harvested
369 [122-123]. The topic of disturbances revolves around three issues: pests and diseases (7 papers), forest fires (3),
370 and storms (2); they are approached through the economic cost and sectoral impacts of prevention measures or *ex-*
371 *post* recovery plans [124-130]. Only a few papers quantified the impacts of forest policy on habitat quality [103,
372 131], and one paper quantifies water quality and quantity implications of climate mitigation policies [132]. They
373 rely on specialized exogenous models, e.g. habitat suitability or hydrology models.

374 Overall, examples of non-timber objectives included in the objective function encompass carbon sequestration,
375 through carbon pricing, and bioenergy production, through market prices and econometrically estimated supply
376 and demand functions. Examples are rarer for other objectives, which are most often only quantified in biophysical
377 units, and either do not enter decision rules or as constraints to the optimisation problem. Some non-timber
378 objectives are notably lacking from our sample. Forest recreation and more generally cultural services are absent,
379 while it is an important topic in the ecosystem services literature [15]. Management for the provision of regulation
380 services is limited to those that directly affect the economic profitability of forest activities, such as pests, fires and
381 storms, and only three papers deal with water services.

382 Natural processes within forestry, especially those related to disturbances, are characterised by a high level of
383 uncertainty [16]. Other uncertainties concern the evolution of prices, trade patterns, as well as parameters estimated
384 for the models [133]. FSM are deterministic models, and uncertainties are traditionally treated by performing
385 sensibility analyses [134]. However, we witnessed that the introduction of uncertainty constitutes a recent, albeit
386 minor focus in FSM research. Three papers use probabilistic approaches such as Monte-Carlo simulation to
387 account for uncertainty [133, 135-136], and one paper is a review dedicated to uncertainty [134]. Other recent
388 contributions focus on re-estimating parameters and assessing the reliability of international databases used for
389 model calibration [137-139].

390 **4.2. Modelling trends and implications**

391 As a consequence of the strong focus on non-timber objectives in recent years, we identify three emerging
392 modelling trends, and discuss the challenges associated to each of them.

393 First, owing to the strong focus on bioenergy and climate issues, many FSM have become specialised models.
394 From 2005 onwards, we witness a multiplication of models where segments of the energy sector are added, and
395 some models have been developed for specific bioenergy markets [36-37]. This implies an increase in model

396 complexity: models must be able to accurately represent biomass feedstocks, processing technologies and energy
397 demand, and require data for model calibration that is both reliable and readily available. For example, the model
398 in Tromborg et al. [140] includes 12 bio-heating technologies and 3 types of biomass from 6 different feedstocks
399 in addition to conventional wood products and industries. Many models have been enhanced to include the above-
400 mentioned carbon accounting modules: these rely on assumptions regarding the carbon content of biomass and
401 harvested wood products, their decay over time, and require information on GHG emissions from various processes
402 as well as substitution coefficients to estimate avoided emissions. Such analyses entail the use of life-cycle-analysis
403 or other methods to assess parameters, on which uncertainties remain [11, 97]. A parallel trend is well-documented
404 for Integrated Assessment Models (IAM) of the energy-climate system which are commonly used to evaluate
405 climate policy. In recent years, many so-called hybrid IAM have been developed, which embed a detailed
406 description of energy-producing technologies within a general top-down aggregated framework [141-142]. Such
407 models face challenges in terms of computational requirements and complexity, theoretical consistency and
408 empirical validity, as well as policy relevance [143]. This last point is of particular importance. Many FSM have
409 become close to biomass-for-bioenergy supply chain models which are increasingly used to investigate the
410 development potential of bioenergy industries and design supply chains at local scales and on generally shorter
411 time horizons [144-145]. While methods and the study object are similar, modellers should keep in mind that
412 despite potential similarities, different models are built to answer different questions. The focus in FSM research
413 should stay on assessing energy policy in the forest sector from a broad, social planner perspective, in particular
414 concerning the articulation with other objectives, traditional timber industries and the availability of forest
415 resources. While this does not exclude technical refinements necessary to an accurate representation of bioenergy
416 production, it entails finding a balance between model complexity and system completeness.

417 Second, the assessment of many non-timber objectives requires detailed, spatially explicit data on environmental
418 conditions. Many FSM were originally developed at the global and national scales, and use aggregated data. We
419 witnessed in our sample a recent trend towards the development of new models with restricted geographical scopes,
420 or the downscaling of already existing models to lower spatial scales. For example, a spatially explicit version of
421 the FFSM was developed from the national model in order to account for variability in environmental conditions
422 [70], and a subnational module was developed for the USA for the Global Forest Products Model [146]. Several
423 new models were created for individual Canadian provinces [147-148], as well as for the Scandinavian region
424 [37]. Several papers we reviewed use Geographical Information System software [121, 149], and the newly
425 developed LURA model uses plot-level forest data and individual plant-level data to produce a very spatially
426 disaggregated model [150]. While earlier studies had to rely on ad-hoc criteria and proxies to model objectives
427 such as conservation, this new generation of FSM is better equipped to handle non-timber objectives.
428 Consequently, we expect the modelling of non-timber objectives to improve as these models develop, and we
429 expect an increasing amount of studies focusing on non-timber objectives, including those still missing today.
430 However, global and national models remain well-equipped to handle issues such as leakages or international trade
431 distortions, and for this reason should not be abandoned [87, 90].

432 Third, many modellers have turned to the use of other, specialised models, coupling them to FSM in order to
433 compensate for their weaknesses and expand the range of analyses possible. The most common type of coupling
434 is established with models in environmental sciences. These include general circulation models to account for
435 climate change [43, 151], landscape succession [101] or habitat quality models [46, 131] to account for
436 environmental impacts, or forest growth simulators and soil models to calculate carbon fluxes [88, 152]. Another
437 common linkage established is with energy models [153] or IAM [113], which is an alternative to the specialisation
438 of FSM described earlier. Our sample also included the use of model couplings to study regulation services, for
439 example with spread models for pathogens [71] or hydrology models [132]. This trend to develop “Economic
440 Environment Integrated Models” is documented in the wider environmental modelling field, and is a welcome
441 development since it enables performing new analyses [154]. However, it also increases complexity for modellers,
442 who are required to ensure compatibility between models in terms of data requirement and their main assumptions.
443 Besides, most couplings are established between a market model (FSM) and models in environmental sciences.
444 While results are more comprehensive with regards to the multiple facets of forestry, interdisciplinary research is
445 not without challenges, which can be both structural and conceptual in nature and should be taken into account
446 when designing research projects [155, 156].

447 4.3. Current frontiers and avenues for future research

448 FSM were originally developed to deal with topics related to timber production and trade at the national and
449 international levels. The recent developments highlighted throughout our review show that FSM have
450 progressively gone beyond their initial purpose by including non-timber objectives related to environmental issues.
451 However, their core structure and target remain the same, which may hinder the investigation of some
452 environmental goals and ecosystem services. The production of bioenergy and carbon sequestration, both
453 contributing to climate change mitigation, are widely studied with FSM. Both objectives relate directly to the
454 original purpose of FSM: projecting timber products supply (in this case, energy products) and projecting forest
455 inventories, and their inclusion only required marginal changes to be made (e.g., estimating new econometric
456 functions, converting timber volumes to carbon, using carbon prices). On the other hand, direct relationships
457 between objectives such habitat conservation or forest recreation and timber inventories or markets are harder to
458 establish, and their full inclusion would require significant changes.

459 Investigating such non-timber objectives often requires modelling the forest sector and forest resources at the local
460 or sub-regional levels. Biophysical and economic assessment studies for many regulation and cultural services
461 often rely on fine scale, spatially explicit data, such as the presence of recreation equipment, landscape viewpoints,
462 topographic data at the local scale, etc. [157]. Even though many FSM are spatialized, they are so at more
463 aggregated levels (e.g. regions) and are ill equipped to handle such information. Modelling such objectives also
464 entails the inclusion of specific management practices (e.g., continuous-cover, close to nature forestry, etc.) as
465 well as releasing the representative economic agent assumption to better represent heterogeneity in behaviours and
466 preferences regarding environmental objectives. FSM were not originally developed to face such challenges, and
467 even when technical refinements are made, data is often lacking to calibrate models such as [33, 70, 158]. Besides,
468 the objective function of most FSM is an economic surplus, which requires non-timber objectives to be monetized
469 and consequently hampers the inclusion of those for which monetary values are hard to estimate. Assessing the
470 economic value of regulation services not linked to markets, and of most cultural services, remains elusive [159].
471 As a consequence, objectives in FSM are often modelled at two levels: some as constraints, others as decision
472 variables within the optimization problem, which implies the precedence of some objectives on others. In some
473 cases, objectives are not quantified, and significant simplifications are made to model objectives located further
474 away from FSM's original targets (e.g., limits on harvests as a proxy for habitat conservation).

475 To improve the integration of non-timber objectives in FSM, future research should focus on building reliable
476 databases of local environmental and economic conditions from which models can be calibrated. Research may
477 also benefit from additional information regarding forest owners' attitudes towards non-timber objectives and their
478 inclusion within traditional forest management practices. Such information could be obtained through surveys,
479 focus groups or laboratory experiments, which also presents the advantage of anchoring research within a
480 stakeholder-oriented dynamic. Once such information is available, an interesting direction to explore is that of
481 Agent-Based Models (ABM). ABM are bottom-up models where dynamics at the system level arise from the
482 combination of and interactions between multiple, individual agent-level decisions. Like traditional FSM, ABM
483 can be based on both economic theory and empirical data, but may be better suited to the investigation of complex
484 social-ecological systems with a high degree of heterogeneity [160-162]. Following the first steps made by
485 Lobianco et al. [33] and Pohjola et al. [163], we believe such a direction could improve the modelling of
486 environmental and behavioural diversity in FSM.

487 Regarding models themselves, the representation of forest resources is of particular importance. While many FSM
488 are able to quantify the resource using multiple strata (e.g., diameter classes, ownership categories, etc.), little
489 attention has been paid to the spatial organization of this resource. Moving from a volume-based description of
490 forest inventories to a landscape-based approach could improve the models' ability to investigate non-timber
491 objectives, in particular those related to regulation and cultural ecosystem services as well as biodiversity. Future
492 efforts could also focus on reformulating the objective function as a multi-objective function where all objectives
493 are integrated in a similar way, and where biophysical units can be used. For example, Yousefpour et al. [164]
494 follow a goal programming approach and use a multi-objective function composed of the Net Present Value for
495 commercial timber production and of carbon sequestration fluxes, to which different weights are attributed. Such

496 multi-objective methods are commonly used in applied forest management [165], and could be developed within
497 and benefit the FSM research field and allow for the inclusion of objectives for which the evaluation of economic
498 value in monetary units is the main limitation.

499 Finally, we have demonstrated that, while FSM research has gone well beyond its original purpose and now
500 routinely addresses climate and environmental issues, publishing dynamics remain centred on specialized journals.
501 Given the current state and orientation of FSM research, as well as the significant importance held by forests in
502 addressing global issues such as climate change and biodiversity erosion, we can only but encourage scholars in
503 the field to communicate their results and methods to the wider environmental and natural resource management
504 modelling field.

505 **5. Conclusions**

506 In this paper, we set out to document and investigate how a particular type of economic simulation models, Forest
507 Sector Models, had been applied to investigate objectives other than their original focus, timber production.
508 Results reveal that FSM have been increasingly used in the last thirty years to investigate environmental objectives.
509 While early applications were dedicated to projecting timber supply and developments in wood products markets,
510 the majority of papers today is concerned with climate change mitigation, through the production of bioenergy
511 and/or carbon sequestration. Biodiversity conservation, the management of disturbances and water regulation
512 services are secondary foci in FSM research, while aspects related to other regulation services and cultural services
513 are absent. We also found out that FSM research has predominantly focused on non-timber objectives that only
514 required marginal changes to be brought to the models. Indeed, while bioenergy production and carbon
515 sequestration directly relate to the original purpose of FSM, e.g., projecting timber supply and timber inventories
516 respectively, modelling objectives such as biodiversity protection or the provision of water services requires the
517 use of spatially explicit data on environmental conditions. Besides, most FSM use total economic surplus as their
518 objective function, which hinders the inclusion of objectives where an economic value in monetary units is hard
519 to estimate. Objectives less commonly studied are often included as constraints to the optimization problem and
520 do not become decision variables, are considered through their negative economic impacts on timber production,
521 or their dynamics are significantly simplified. These approaches assume precedence of some objectives on others,
522 and lead to the exclusion of many non-market benefits associated to ecosystem services. In recent years, research
523 in the field has turned to the development of models with restricted geographical scopes in order to better take into
524 account local conditions, as well as to the establishment of couplings with specialized models (e.g., ecological,
525 hydrology, energy models etc.) which enable a more comprehensive and realistic representation of non-timber
526 objectives. While these developments expand the range of analyses that can be performed with FSM and enable
527 overcoming some of the abovementioned limitations, they also increase model complexity, entail the use of
528 additional data for calibration, and require researchers to perform multidisciplinary research and to ensure the
529 consistency and compatibility of the various methods used.

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