



**HAL**  
open science

# **Evolving Integrated Models From Narrower Economic Tools: the Example of Forest Sector Models**

Miguel Riviere, Sylvain Caurla, Philippe Delacote

► **To cite this version:**

Miguel Riviere, Sylvain Caurla, Philippe Delacote. Evolving Integrated Models From Narrower Economic Tools: the Example of Forest Sector Models. *Environmental Modeling & Assessment*, 2020, 25 (4), pp.453-469. 10.1007/s10666-020-09706-w . hal-02512330

**HAL Id: hal-02512330**

**<https://hal.univ-lorraine.fr/hal-02512330>**

Submitted on 10 Sep 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

[Click here to view linked References](#)

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

2 **Miguel RIVIERE<sup>a,\*</sup>**, Sylvain CAURLA<sup>a</sup>, Philippe DELACOTE<sup>a,b</sup>

3 <sup>a</sup>: *Université de Lorraine, Université de Strasbourg, AgroParisTech, CNRS, INRAE, BETA, 54000, Nancy, France*

4 <sup>b</sup>: *Climate Economics Chair, Univ. Paris Dauphine, Paris, France*

5 <sup>\*</sup>: Corresponding author: [miguel.riviere@agroparistech.fr](mailto:miguel.riviere@agroparistech.fr). BETA, Campus AgroParisTech, 14 rue Girardet, 54042  
6 Nancy cedex, France. +33 3 83 39 68 58

## 7 **ORCID:**

- 8 • Miguel Riviere: 0000-0003-3469-9588
- 9 • Sylvain Caurla: 0000-0002-8785-7079
- 10 • Philippe Delacote: 0000-0002-9888-7193

## 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

## 32 **Acknowledgements**

33 This work was supported by the French Ministère de l'Agriculture et de l'Alimentation. The BETA contributes to  
34 the LabEX ARBRE ANR-11-LABX-0002-01. This research is part of the Agriculture and Forestry research  
35 program by the Climate Economics Chair. The authors want to thank the Climate Economics Chair for financial  
36 support. The authors want to thank Pr. Harold Levrel for his attentive help, as well as our anonymous reviewers  
37 for their insightful comments and suggestions.

## 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.  $\beta_k$  and  $\alpha_k$  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)
<b>Production of goods</b> - Industrial roundwood - Fuelwood (bio-energy) - Non-wood forest products	Raw materials (including timber and non-timber products) Food production
<b>Protection of soil and water</b> - 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
<b>Conservation of biodiversity</b>	Genetic resources
<b>Provision of social services</b> - 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)
<b>Multiple-use</b> (several objectives with none significantly more important than the others)	
<b>Other</b> (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 VOSviewer<sup>1</sup> [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

---

<sup>1</sup> 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 areas<sup>2</sup> 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

<sup>2</sup> 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<sup>a</sup>

215 <sup>a</sup> 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.



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

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

### 282 **3.3. How does the inclusion of non-timber objectives affect the models?**

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

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

304 Then, the inclusion of carbon sequestration into FSM can take two routes. Firstly, it can be introduced as an  
305 objective through monetisation and subsequent addition to the objective function. A price is given in monetary  
306 units per ton of carbon, many estimates being available in the literature [2]. Landowners receive a yearly payment  
307 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  $t$ ,  $\Delta C_t$  the change in carbon stock

308 between years  $t$  and  $t-1$ , and  $\Delta C_t^{BAU}$  the stock change in a baseline scenario<sup>3</sup>. 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  $\omega_k$  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  $\Delta C_t^f$  and  $\Delta C_t^p$  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.

<sup>3</sup> In some cases, all carbon sequestered is subsidized, and the  $\Delta C_t^{BAU}$  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.

531 **References**

- 532 [1] V. Masson-Delmotte *et al.*, “Global warming of 1.5°C An IPCC Special Report on the impacts of global warming of 1.5°C above  
533 pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to  
534 the threat of climate change, sustainable development, and efforts to eradicate poverty Summary for Policymakers Edited by  
535 Science Officer Science Assistant Graphics Officer Working Group I Technical Support Unit,” Geneva, 2018.
- 536 [2] J. Rogelj *et al.*, “Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development,” in *Global Warming of  
537 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global  
538 greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*, [Masson-  
539 Delmotte, S. C. V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock,  
540 and T. W. (eds. . J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, Eds. In press, 2018.
- 541 [3] S. Diaz *et al.*, “Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the  
542 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services-ADVANCE UNEDITED VERSION-  
543 Members of the management committee who provid,” 2019.
- 544 [4] S. H. Hamilton, S. Elsworth, J. H. A. Guillaume, A. J. Jakeman, and S. A. Pierce, “Environmental Modelling & Software Integrated  
545 assessment and modelling : Overview and synthesis of salient dimensions,” *Environ. Model. Softw.*, vol. 64, pp. 215–229, 2015.
- 546 [5] H. Van Delden, R. Seppelt, R. White, and A. J. Jakeman, “A methodology for the design and development of integrated models for  
547 policy support,” *Environ. Model. Softw.*, vol. 26, no. 3, pp. 266–279, 2011.
- 548 [6] G. Harris, “Integrated assessment and modelling : an essential way of doing science 1,” *Environ. Model. Softw.*, vol. 17, pp. 201–  
549 207, 2002.
- 550 [7] L. J. Aznar-Sánchez, José A Belmonte-Ureña, M. J. López-Serrano, and J. F. Velasco-Muñoz, “Forest Ecosystem Services: An  
551 Analysis of Worldwide Research,” *forests*, vol. 9, pp. 1–19, 2018.
- 552 [8] H. Tian *et al.*, “Global patterns and controls of soil organic carbon dynamics as simulated by multiple terrestrial biosphere models:  
553 Current status and future directions,” *Global Biogeochem. Cycles*, vol. 29, no. 6, pp. 775–792, 2015.
- 554 [9] R. A. Sedjo and B. Sohngen, “Carbon Sequestration in Forests and Soils,” *Ssrn*, 2012.
- 555 [10] E. Eriksson *et al.*, “Integrated carbon analysis of forest management practices and wood substitution,” *Can. J. For. Res.*, vol. 37,  
556 no. 3, pp. 671–681, Mar. 2007.
- 557 [11] H. K. Sjølie and B. Solberg, “Greenhouse gas emission impacts of use of Norwegian wood pellets: a sensitivity analysis,” *Environ.  
558 Sci. Policy*, vol. 14, no. 8, pp. 1028–1040, Dec. 2011.
- 559 [12] R. N. Sturrock *et al.*, “Climate change and forest diseases,” *Plant Pathol.*, vol. 60, no. 1, pp. 133–149, Feb. 2011.
- 560 [13] S. Broadmeadow and T. R. Nisbet, “The effects of riparian forest management on the freshwater environment: a literature review  
561 of best management practice,” *Hydrol. Earth Syst. Sci.*, vol. 8, no. 3, pp. 286–305, 2010.
- 562 [14] A. I. Milcu, J. Hanspach, D. Abson, and J. Fischer, “Cultural ecosystem services: A literature review and prospects for future  
563 research,” *Ecol. Soc.*, vol. 18, no. 3, p. art44, Sep. 2013.
- 564 [15] M. Hernández-Morcillo, T. Plieninger, and C. Bieling, “An empirical review of cultural ecosystem service indicators,” *Ecological  
565 Indicators*, vol. 29. Elsevier, pp. 434–444, 01-Jun-2013.
- 566 [16] M. Hanewinkel, S. Hummel, and A. Albrecht, “Assessing natural hazards in forestry for risk management: A review,” *European  
567 Journal of Forest Research*, vol. 130, no. 3, pp. 329–351, 2011.
- 568 [17] S. García, J. Abildtrup, and A. Stenger, “How does economic research contribute to the management of forest ecosystem  
569 services?,” *Ann. For. Sci.*, vol. 75, no. 2, p. 53, 2018.
- 570 [18] P. Duncker *et al.*, “How Forest Management affects Ecosystem Services, including Timber Production and Economic Return:  
571 Synergies and Trade-Offs,” *Ecol. Soc.*, vol. 17, no. 4, p. art50, Dec. 2012.
- 572 [19] FAUSTMANN and M., “Berechnung des Werthes, welchen Waldboden, sowie noch nicht haubare Holzbestände für die  
573 Waldwirtschaft besitzen [Calculation of the value which forest land and immature stands possess for forestry],” *Allg. Forst- und  
574 Jagd-Zeitung*, vol. 25, pp. 441–455, 1849.
- 575 [20] R. Hartman, “THE HARVESTING DECISION WHEN A STANDING FOREST HAS VALUE,” *Econ. Inq.*, vol. XIV, no. March,  
576 pp. 52–58, 1976.
- 577 [21] L. Tardieu, “The need for integrated spatial assessments in ecosystem service mapping,” *Rev. Agric. Food Environ. Stud.*, vol. 98,  
578 no. 3, pp. 173–200, 2017.
- 579 [22] J. Maes *et al.*, “Mapping ecosystem services for policy support and decision making in the European Union,” *Ecosyst. Serv.*, vol. 1,  
580 no. 1, pp. 31–39, Jul. 2012.
- 581 [23] L. Diaz-Balteiro and C. Romero, “Making forestry decisions with multiple criteria: A review and an assessment,” *Forest Ecology  
582 and Management*, vol. 255, no. 8–9. Elsevier, pp. 3222–3241, 15-May-2008.
- 583 [24] B. Uhde, A. Hahn, V. C. Griess, and T. Knoke, “Hybrid MCDA Methods to Integrate Multiple Ecosystem Services in Forest  
584 Management Planning: A Critical Review,” *Environ. Manage.*, vol. 56, no. 2, pp. 373–388, Aug. 2015.
- 585 [25] M. Buchy and S. Hoverman, “Understanding public participation in forest planning: a review,” *For. Policy Econ.*, vol. 1, no. 1, pp.  
586 15–25, May 2000.
- 587 [26] A. Ficko, G. Lidestav, Á. Ní Dhubháin, H. Karppinen, I. Zivojinovic, and K. Westin, “European private forest owner typologies: A  
588 review of methods and use,” *Forest Policy and Economics*, vol. 99. Elsevier, pp. 21–31, 01-Feb-2019.
- 589 [27] D. M. Adams and R. W. Haynes, *Resource and market projections for forest policy development : twenty-five years of experience  
590 with the U.S. RPA timber assessment*. Springer, 2007.
- 591 [28] G. S. Latta, H. K. Sjølie, and B. Solberg, “A review of recent developments and applications of partial equilibrium models of the  
592 forest sector,” *J. For. Econ.*, vol. 19, no. 4, pp. 350–360, Dec. 2013.
- 593 [29] S. Northway, G. Q. Bull, and J. D. Nelson, “Forest sector partial equilibrium models: Processing components,” *For. Sci.*, vol. 59,  
594 no. 2, pp. 151–156, Apr. 2013.
- 595 [30] J. Buongiorno, “Global modelling to predict timber production and prices: The GFPM approach,” *Forestry*, vol. 88, no. 3, pp. 291–  
596 303, 2014.
- 597 [31] A. Toppinen and J. Kuuluvainen, “Forest sector modelling in Europe-the state of the art and future research directions,” *For.  
598 Policy Econ.*, vol. 12, no. 1, pp. 2–8, 2010.
- 599 [32] B. Solberg, “Forest sector simulation models as methodological,” *Silva Fennica*, vol. 20, no. 4. pp. 419–427, 1986.
- 600 [33] A. Lobianco, P. Delacote, S. Cauria, and A. Barkaoui, “Accounting for Active Management and Risk Attitude in Forest Sector  
601 Models An Impact Study on French Forests,” *Env. Model Assess*, vol. 21, pp. 391–405, 2016.

- 602 [34] H. K. Sjølie, G. S. Latta, T. Gobakken, and B. Solberg, "NorFor - a forest sector model of Norway Model overview and structure," *INA fagrapport 18. Department of Ecology and Natural Resource Management Norwegian University of Life Sciences*. 2011.
- 603 [35] C. Johnston and G. C. van Kooten, "Modelling Bi-lateral Forest Product Trade Flows : Experiencing Vertical and Horizontal Chain," no. August, 2014.
- 604 [36] A. M. I. Kallio, P. Anttila, M. McCormick, and A. Asikainen, "Are the Finnish targets for the energy use of forest chips realistic- Assessment with a spatial market model," *J. For. Econ.*, vol. 17, no. 2, pp. 110–126, 2011.
- 605 [37] W. F. Mustapha, E. Trømborg, and T. F. Bolkesjø, "Forest-based biofuel production in the Nordic countries: Modelling of optimal allocation," *For. Policy Econ.*, no. September 2016, pp. 1–10, 2017.
- 606 [38] S. Caurla, P. Delacote, F. Lecocq, J. Barthès, and A. Barkaoui, "Combining an inter-sectoral carbon tax with sectoral mitigation policies: Impacts on the French forest sector," *J. For. Econ.*, vol. 19, no. 4, pp. 450–461, 2013.
- 607 [39] D. Adams, B. A. Mccarl, and B. C. Murray, "FASOMGHG Conceptual Structure, and Specification: Documentation," 2005.
- 608 [40] R. Hänninen and A. M. I. Kallio, "Economic impacts on the forest sector of increasing forest biodiversity conservation in Finland," *Silva Fenn.*, vol. 41, no. 3, pp. 507–523, 2007.
- 609 [41] C. Rafal, R. C. Abt, R. Jonsson, J. P. Prestemon, and F. W. Cubbage, "Modeling the Impacts of EU Bioenergy Demand on the Forest Sector of the Southeast U.S.," *J. Energy Power Eng.*, vol. 7, pp. 1073–1081, 2013.
- 610 [42] A. M. I. Kallio, A. Moiseyev, B. Solberg, and a M. I. Kallio Moiseyev, A., Solberg, B., "The global forest sector model EFI-GTM. The model structure," 2004.
- 611 [43] A. Favero, R. Mendelsohn, and B. Sohngen, "Can the Global Forest Sector Survive 11 °C Warming?," *Agric. Resour. Econ. Rev.*, vol. 47, no. 2, pp. 388–413, Aug. 2018.
- 612 [44] P. Schwarzbauer and E. Rametsteiner, "The impact of SFM-certification on forest product markets in Western Europe - An analysis using a forest sector simulation model," *For. Policy Econ.*, vol. 2, no. 3–4, pp. 241–256, 2001.
- 613 [45] P. A. Samuelson, "Spatial price equilibrium and linear programming," *Am. Econ. Rev.*, vol. 42, no. 3, pp. 283–303, 1952.
- 614 [46] A. M. I. Kallio, R. Hänninen, N. Vainikainen, and S. Luque, "Biodiversity value and the optimal location of forest conservation sites in Southern Finland," *Ecol. Econ.*, vol. 67, no. 2, pp. 232–243, 2008.
- 615 [47] H. K. Sjølie, G. S. Latta, D. M. Adams, and B. Solberg, "Impacts of agent information assumptions in forest sector modeling," *J. For. Econ.*, vol. 17, no. 2, pp. 169–184, 2011.
- 616 [48] C. M. T. Johnston and G. C. van Kooten, "Global trade impacts of increasing Europe's bioenergy demand," *J. For. Econ.*, vol. 23, pp. 27–44, 2016.
- 617 [49] S. Caurla, F. Lecocq, P. Delacote, and A. Barkaoui, "The French Forest Sector Model: version 1.0.," 2010.
- 618 [50] J. Buongiorno, "Forest sector modeling: A synthesis of econometrics, mathematical programming, and system dynamics methods," *Int. J. Forecast.*, vol. 12, no. 3, pp. 329–343, 1996.
- 619 [51] P. Bettinger, K. Boston, J. P. Siry, and D. L. Grebner, "Management of Forests and Other Natural Resources," *For. Manag. Plan.*, pp. 1–20, 2017.
- 620 [52] S. M. Carvalho-Ribeiro, A. Lovett, and T. O'Riordan, "Multifunctional forest management in Northern Portugal: Moving from scenarios to governance for sustainable development," *Land use policy*, vol. 27, no. 4, pp. 1111–1122, Oct. 2010.
- 621 [53] G. R. Hall, "The myth and reality of multiple use forestry," *Nat. Resour. J.*, vol. 2, pp. 276–290, 1963.
- 622 [54] Ü. Mander, H. Wiggering, and K. Helming, *Multifunctional land use: Meeting future demands for landscape goods and services*. Springer, 2007.
- 623 [55] MCEPF, "RESOLUTION H1 General Guidelines for the Sustainable Management of Forests in Europe," *Second Minist. Conf. Prot. For. Eur. 16-17 June 1993*, no. June, pp. 1–5, 1993.
- 624 [56] FAO, "FRA 2015 - Terms and Definitions," 2012.
- 625 [57] FAO, "Terms and Definitions FRA 2020," 2018.
- 626 [58] D. J. Krieger, *The economic values of forest ecosystem services: a review. The Wilderness Society*. 2001.
- 627 [59] TEEB, "The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A synthesis of the approach, conclusions and recommendations of TEEB," 2010.
- 628 [60] R. Haines-Young and M. B. Potschin, "Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure," 2018.
- 629 [61] G. M. Mace, K. Norris, and A. H. Fitter, "Biodiversity and ecosystem services: a multilayered relationship," *Trends Ecol. Evol.*, vol. 27, no. 1, pp. 19–26, Jan. 2012.
- 630 [62] P. Põllumäe, H. Korjus, and T. Paluots, "Management motives of Estonian private forest owners," *For. Policy Econ.*, vol. 42, pp. 8–14, May 2014.
- 631 [63] M. A. Côté, A. Généreux-Tremblay, D. Gilbert, and N. Gélinas, "Comparing the profiles, objectives and behaviours of new and longstanding non-industrial private forest owners in Quebec, Canada," *For. Policy Econ.*, vol. 78, pp. 116–121, May 2017.
- 632 [64] P. Kumer and E. Štrumbelj, "Clustering-based typology and analysis of private small-scale forest owners in Slovenia," *For. Policy Econ.*, vol. 80, pp. 116–124, Jul. 2017.
- 633 [65] M. Hugosson and F. Ingemarson, "Objectives and motivations of small-scale forest owners; theoretical modelling and qualitative assessment," *Silva Fennica*, vol. 38, no. 2, pp. 217–231, 2004.
- 634 [66] J. Kuuluvainen, H. Karppinen, and V. Ovaskainen, "Landowner objectives and nonindustrial private timber supply," *For. Sci.*, vol. 42, no. 3, pp. 300–309, 1996.
- 635 [67] D. N. Wear and J. W. Coulston, "Specifying Forest Sector Models for Forest Carbon Projections," *J. For. Econ.*, vol. 34, no. 1–2, pp. 73–97, 2019.
- 636 [68] N. J. Van Eck and L. Waltman, "VOSviewer Manual," 2018.
- 637 [69] N. J. van Eck and L. Waltman, "Software survey: VOSviewer, a computer program for bibliometric mapping," *Scientometrics*, vol. 84, no. 2, pp. 523–538, 2010.
- 638 [70] A. Lobianco, P. Delacote, S. Caurla, and A. Barkaoui, "The importance of introducing spatial heterogeneity in bio-economic forest models: Insights gleaned from FFSM++," *Ecol. Modell.*, vol. 309–310, pp. 82–92, 2015.
- 639 [71] C. Petucco, A. Lobianco, and S. Caurla, "Economic Evaluation of an Invasive Forest Pathogen at a Large Scale: The Case of Ash Dieback in France," *Environ. Model. Assess.*, 2019.
- 640 [72] S. Härkönen *et al.*, "Environmental Modelling & Software A climate-sensitive forest model for assessing impacts of forest management in Europe," *Environ. Model. Softw.*, vol. 115, no. August 2018, pp. 128–143, 2019.
- 641 [73] J. Buongiorno, S. Zhu, D. Zhang, J. Turner, and D. Tomberlin, *The Global Forest Products Model*. Academic, 2003.
- 642 [74] R. C. Abt, F. W. Cubbage, and Pacheco, "SOUTHERN FOREST RESOURCE ASSESSMENT USING THE SUBREGIONAL TIMBER SUPPLY (SRTS) MODEL," *For. Prod. J.*, vol. 50, no. 4, pp. 25–25, Apr. 2000.
- 643 [75] A. Moiseyev, B. Solberg, B. Michie, and A. M. I. Kallio, "Modeling the impacts of policy measures to prevent import of illegal wood and wood products," *For. Policy Econ.*, vol. 12, no. 1, pp. 24–30, 2010.
- 644 [76] R. Li, J. Buongiorno, J. A. Turner, S. Zhu, and J. Prestemon, "Long-term effects of eliminating illegal logging on the world forest



- 678 industries, trade, and inventory,” *For. Policy Econ.*, vol. 10, no. 7–8, pp. 480–490, 2008.
- 679 [77] A. Mosnier *et al.*, “Modeling Impact of Development Trajectories and a Global Agreement on Reducing Emissions from  
680 Deforestation on Congo Basin Forests by 2030,” *Environ. Resour. Econ.*, vol. 57, no. 4, pp. 505–525, Apr. 2014.
- 681 [78] X. Zhang, B. Xu, L. Wang, A. Yang, and H. Yang, “Eliminating illegal timber consumption or production: Which is the more  
682 economical means to reduce illegal logging?,” *Forests*, vol. 7, no. 9, 2016.
- 683 [79] P. M. Fernandes *et al.*, “Prescribed burning in southern Europe: Developing fire management in a dynamic landscape,” *Frontiers  
684 in Ecology and the Environment*, vol. 11, no. SUPPL. 1. 2013.
- 685 [80] A. Lobianco, S. Cauria, P. Delacote, and A. Barkaoui, “Carbon mitigation potential of the French forest sector under threat of  
686 combined physical and market impacts due to climate change,” *J. For. Econ.*, vol. 23, pp. 4–26, 2016.
- 687 [81] E. Trømborg and H. K. Sjølie, “Data applied in the forest sector models NorFor and NTMIII,” *Ina fagrapport. Dep. Ecol. Nat.  
688 Resour. Manag. Nor. Univ. Life Sci.*, vol. 17, 2011.
- 689 [82] A. M. I. Kallio, O. Salminen, and R. Sievänen, “Sequester or substitute-Consequences of increased production of wood based  
690 energy on the carbon balance in Finland,” *J. For. Econ.*, vol. 19, no. 4, pp. 402–415, 2013.
- 691 [83] H. K. Sjølie, G. S. Latta, and B. Solberg, “Potentials and costs of climate change mitigation in the Norwegian forest sector - Does  
692 choice of policy matter?,” *Can. J. For. Res. Can. Rech. For.*, vol. 43, no. 6, pp. 589–598, 2013.
- 693 [84] E. H. Im, D. M. Adams, and G. S. Latta, “Potential impacts of carbon taxes on carbon flux in western Oregon private forests,” *For.  
694 Policy Econ.*, vol. 9, no. 8, pp. 1006–1017, 2007.
- 695 [85] G. Latta, D. M. Adams, R. J. Alig, and E. White, “Simulated effects of mandatory versus voluntary participation in private forest  
696 carbon offset markets in the United States,” *J. For. Econ.*, vol. 17, no. 2, pp. 127–141, 2011.
- 697 [86] F. Lecocq, S. Cauria, P. Delacote, A. Barkaoui, and A. Sauquet, “Paying for forest carbon or stimulating fuelwood demand?  
698 Insights from the French Forest Sector Model,” *J. For. Econ.*, vol. 17, no. 2, pp. 157–168, 2011.
- 699 [87] J. Buongiorno and S. Zhu, “Consequences of carbon offset payments for the global forest sector,” *J. For. Econ.*, vol. 19, no. 4, pp.  
700 384–401, 2013.
- 701 [88] E. H. Im, D. M. Adams, and G. S. Latta, “The impacts of changes in federal timber harvest on forest carbon sequestration in  
702 western Oregon,” *Can. J. For. Res. Can. Rech. For.*, vol. 40, no. 9, pp. 1710–1723, 2010.
- 703 [89] A. M. I. Kallio, B. Solberg, L. Käär, and R. Päivinen, “Forest Policy and Economics Economic impacts of setting reference levels  
704 for the forest carbon sinks in the EU on the European forest sector,” *For. Policy Econ.*, vol. 92, no. May, pp. 193–201, 2018.
- 705 [90] A. M. I. Kallio and B. Solberg, “Leakage of forest harvest changes in a small open economy: case Norway,” *Scandinavian Journal  
706 of Forest Research*, vol. 33, no. 5, pp. 502–510, 2018.
- 707 [91] T. Bolkesjø, E. Trømborg, and B. Solberg, “Bioenergy from the forest sector: Economic potential and interactions with timber and  
708 forest products markets in Norway,” *Scand. J. For. Res.*, vol. 21, no. 2, pp. 175–185, 2006.
- 709 [92] A. Moiseyev, B. Solberg, A. M. I. Kallio, and M. Lindner, “An economic analysis of the potential contribution of forest biomass to  
710 the EU RES target and its implications for the EU forest industries,” *J. For. Econ.*, vol. 17, no. 2, pp. 197–213, 2011.
- 711 [93] E. M. White, G. Latta, R. J. Alig, K. E. Skog, and D. M. Adams, “Biomass production from the U.S. forest and agriculture sectors  
712 in support of a renewable electricity standard,” *Energy Policy*, vol. 58, pp. 64–74, Jul. 2013.
- 713 [94] S. Cauria, P. Delacote, F. Lecocq, and A. Barkaoui, “Stimulating fuelwood consumption through public policies: An assessment of  
714 economic and resource impacts based on the French Forest Sector Model,” *Energy Policy*, vol. 63, pp. 338–347, 2013.
- 715 [95] H. L. Kangas, J. Lintunen, J. Pohjola, L. Hetemäki, and J. Uusivuori, “Investments into forest biorefineries under different price  
716 and policy structures,” *Energy Econ.*, vol. 33, no. 6, pp. 1165–1176, 2011.
- 717 [96] H. K. Sjølie, E. Trømborg, B. Solberg, and T. F. Bolkesjø, “Effects and costs of policies to increase bioenergy use and reduce  
718 GHG emissions from heating in Norway,” *For. Policy Econ.*, vol. 12, no. 1, pp. 57–66, 2010.
- 719 [97] J. M. Earles, A. Halog, P. Ince, and K. Skog, “Integrated Economic Equilibrium and Life Cycle Assessment Modeling for Policy-  
720 based Consequential LCA,” 2012.
- 721 [98] H. Böttcher, S. Frank, P. Havlík, and B. Elbersen, “Future GHG emissions more efficiently controlled by land-use policies than by  
722 bioenergy sustainability criteria,” *Biofuels, Bioprod. Biorefining*, vol. 7, no. 2, pp. 115–125, Mar. 2013.
- 723 [99] P. Havlík *et al.*, “Global land-use implications of first and second generation biofuel targets,” *Energy Policy*, vol. 39, no. 10, pp.  
724 5690–5702, 2011.
- 725 [100] S. U. Okoro, U. Schickhoff, and U. A. Schneider, “Impacts of bioenergy policies on land-use change in Nigeria,” *Energies*, vol. 11,  
726 no. 1, p. 152, Jan. 2018.
- 727 [101] J. K. Costanza, R. C. Abt, A. J. McKerrow, and J. A. Collazo, “Bioenergy production and forest landscape change in the  
728 southeastern United States,” *GCB Bioenergy*, vol. 9, no. 5, pp. 924–939, May 2017.
- 729 [102] A. S. Duden *et al.*, “Modeling the impacts of wood pellet demand on forest dynamics in southeastern United States,” *Biofuels,  
730 Bioprod. Biorefining*, vol. 11, no. 6, pp. 1007–1029, Nov. 2017.
- 731 [103] E. Gejjer, J. Andersson, G. Bostedt, R. Brännlund, and J. Hjäältén, “Safeguarding species richness vs. increasing the use of  
732 renewable energy—The effect of stump harvesting on two environmental goals,” *J. For. Econ.*, vol. 20, pp. 111–125, 2014.
- 733 [104] C. Schleupner and U. A. Schneider, “Effects of bioenergy policies and targets on European wetland restoration options,” *Environ.  
734 Sci. Policy*, vol. 13, no. 8, pp. 721–732, 2010.
- 735 [105] E. Gejjer, G. Bostedt, and R. Brännlund, “Damned if you do, damned if you do not-Reduced Climate Impact vs. Sustainable  
736 Forests in Sweden,” *Resour. Energy Econ.*, vol. 33, no. 1, pp. 94–106, 2011.
- 737 [106] J. Perez-Garcia, L. A. Joyce, and A. D. McGuire, “Temporal uncertainties of integrated ecological/economic assessments at the  
738 global and regional scales,” *For. Ecol. Manage.*, vol. 162, no. 1, pp. 105–115, 2002.
- 739 [107] B. Solberg, A. Moiseyev, and A. M. I. Kallio, “Economic impacts of accelerating forest growth in Europe,” *For. Policy Econ.*, vol.  
740 5, no. 2, pp. 157–171, 2003.
- 741 [108] R. H. Beach *et al.*, “Climate change impacts on US agriculture and forestry: Benefits of global climate stabilization,” *Environ. Res.  
742 Lett.*, vol. 10, no. 9, 2015.
- 743 [109] G. C. van Kooten and C. Johnston, “The Economics of Forest Carbon Offsets,” *Ssm*, no. April, pp. 1–20, 2016.
- 744 [110] D. M. Adams, R. Alig, G. Latta, and E. M. White, “Regional Impacts of a Program for Private Forest Carbon Offset Sales,” *J. For.,  
745 vol. 109, no. 8, pp. 444–461, 2011.*
- 746 [111] H. K. Sjølie, G. S. Latta, and B. Solberg, “Impacts of the Kyoto Protocol on boreal forest climate change mitigation,” *Ann. For.  
747 Sci.*, vol. 71, no. 2, pp. 267–277, 2014.
- 748 [112] A. Moiseyev, B. Solberg, and A. M. I. Kallio, “The impact of subsidies and carbon pricing on the wood biomass use for energy in  
749 the EU,” *Energy*, vol. 76, pp. 161–167, 2014.
- 750 [113] M. Tavoni, B. Sohngen, and V. Bosetti, “Forestry and the carbon market response to stabilize climate,” *Energy Policy*, vol. 35, no.  
751 11, pp. 5346–5353, 2007.
- 752 [114] A. Favero and R. Mendelsohn, “Using Markets for Woody Biomass Energy to Sequester Carbon in Forests,” *J. Assoc. Environ.  
753 Resour. Econ.*, vol. 1, no. 1/2, pp. 75–95, 2014.

- 754 [115] G. Latta, D. M. Adams, R. J. Alig, and E. White, "Simulated effects of mandatory versus voluntary participation in private forest  
755 carbon offset markets in the United States," *J. For. Econ.*, vol. 17, pp. 127–141, 2011.
- 756 [116] A. M. I. Kallio, A. Moiseyev, and B. Solberg, "Economic impacts of increased forest conservation in Europe: a forest sector model  
757 analysis," *Environ. Sci. Policy*, vol. 9, no. 5, pp. 457–465, 2006.
- 758 [117] T. F. Bolkesjø, E. Trømborg, and B. Solberg, "Increasing forest conservation in Norway: Consequences for timber and forest  
759 products markets," *Environ. Resour. Econ.*, vol. 31, no. 1, pp. 95–115, 2005.
- 760 [118] F. Merry, B. Soares-Filho, D. Nepstad, G. Amacher, and H. Rodrigues, "Balancing conservation and economic sustainability: The  
761 future of the amazon timber industry," *Environ. Manage.*, vol. 44, no. 3, pp. 395–407, 2009.
- 762 [119] E. B. Barbier, N. Bockstael, J. C. Burgess, and I. Strand, "The Linkages between the Timber Trade and Tropical  
763 Deforestation???Indonesia," *World Econ.*, vol. 18, no. 3, pp. 411–442, May 1995.
- 764 [120] L. Sun and B. E. C. Bogdanski, "Trade incentives for importers to adopt policies to address illegally logged timber: The case of  
765 non-tropical hardwood plywood," *J. For. Econ.*, vol. 27, pp. 18–27, 2017.
- 766 [121] C. Schlepner and U. A. Schneider, "Allocation of European wetland restoration options for systematic conservation planning,"  
767 *Land use policy*, vol. 30, pp. 604–614, 2013.
- 768 [122] D. M. Adams and G. S. Latta, "Timber trends on private lands in western Oregon and Washington: a new look," *West. J. Appl.  
769 For.*, vol. 22, pp. 8–14, 2007.
- 770 [123] D. M. Adams and G. S. Latta, "Future Prospects for Private Timber Harvest in Eastern Oregon," *WEST.J.APPL.FOR.*, vol. 22, no.  
771 3, 2007.
- 772 [124] D. M. Adams and G. S. Latta, "Costs and regional impacts of restoration thinning programs on the national forests in eastern  
773 Oregon," *Can. J. For. Res.*, vol. 35, no. 6, pp. 1319–1330, 2005.
- 774 [125] P. J. Ince, H. Spelter, K. E. Skog, A. Kramp, and D. P. Dykstra, "Market impacts of hypothetical fuel treatment thinning programs  
775 on federal lands in the western United States," *For. Policy Econ.*, vol. 10, no. 6, pp. 363–372, Aug. 2008.
- 776 [126] J. P. Prestemon, K. L. Abt, and R. J. Huggett, "Market impacts of a multiyear mechanical fuel treatment program in the U.S.," *For.  
777 Policy Econ.*, vol. 10, no. 6, pp. 386–399, 2008.
- 778 [127] J. A. Turner, J. Buongiorno, S. Zhu, J. P. Prestemon, R. Li, and L. S. Bulman, "Modelling the impact of the exotic forest pest  
779 Nectria on the New Zealand forest sector and its major trading partners," *New Zeal. J. For. Sci.*, vol. 37, no. 3, pp. 383–411, 2007.
- 780 [128] C. Sun, "Timber Market Recovery after a Hurricane," *For. Sci.*, vol. 62, no. 6, pp. 600–612, Dec. 2016.
- 781 [129] S. Caurla, S. Garcia, and A. Niedzwiedz, "Store or export? An economic evaluation of financial compensation to forest sector after  
782 windstorm. The case of Hurricane Klaus," *For. Policy Econ.*, vol. 61, pp. 30–38, 2015.
- 783 [130] J. P. Prestemon, K. L. Abt, K. M. Potter, and F. H. Koch, "An economic assessment of mountain pine beetle timber salvage in the  
784 west," *West. J. Appl. For.*, vol. 28, no. 4, pp. 143–153, 2013.
- 785 [131] S. K. Pattanayak *et al.*, "Forest forecasts: Does individual heterogeneity matter for market and landscape outcomes?," *For. Policy  
786 Econ.*, vol. 6, no. 3–4, pp. 243–260, 2004.
- 787 [132] C.-H. Yu, B. McCarl, C.-H. Yu, and B. A. McCarl, "The Water Implications of Greenhouse Gas Mitigation: Effects on Land Use,  
788 Land Use Change, and Forestry," *Sustainability*, vol. 10, no. 7, p. 2367, Jul. 2018.
- 789 [133] A. M. I. Kallio, "Accounting for uncertainty in a forest sector model using Monte Carlo simulation," *For. Policy Econ.*, vol. 12, no.  
790 1, pp. 9–16, 2010.
- 791 [134] R. P. Chudy, H. K. Sjølie, and B. Solberg, "Incorporating risk in forest sector modeling – state of the art and promising paths for  
792 future research," *Scandinavian Journal of Forest Research*, vol. 31, no. 7, pp. 719–727, 02-Oct-2016.
- 793 [135] J. Buongiorno and C. Johnston, "Effects of parameter and data uncertainty on long-term projections in a model of the global forest  
794 sector," *For. Policy Econ.*, vol. 93, no. May, pp. 10–17, 2018.
- 795 [136] E. O. Jåstad, W. F. Mustapha, T. F. Bolkesjø, E. Trømborg, and B. Solberg, "Modelling of uncertainty in the economic  
796 development of the Norwegian forest sector," *J. For. Econ.*, vol. 32, no. May 2017, pp. 106–115, 2018.
- 797 [137] C. Morland, F. Schier, N. Janzen, and H. Weimar, "Supply and demand functions for global wood markets: Specification and  
798 plausibility testing of econometric models within the global forest sector," *For. Policy Econ.*, vol. 92, pp. 92–105, Jul. 2018.
- 799 [138] P. Rougieux and O. Damette, "Reassessing forest products demand functions in Europe using a panel cointegration approach,"  
800 *Appl. Econ.*, vol. 50, no. 30, pp. 3247–3270, 2018.
- 801 [139] A. Kallio, B. Solberg, A. M. I. Kallio, and B. Solberg, "On the Reliability of International Forest Sector Statistics: Problems and  
802 Needs for Improvements," *Forests*, vol. 9, no. 7, p. 407, Jul. 2018.
- 803 [140] E. Trømborg, T. F. Bolkesjø, and B. Solberg, "Impacts of policy means for increased use of forest-based bioenergy in Norway-A  
804 spatial partial equilibrium analysis," *Energy Policy*, vol. 35, no. 12, pp. 5980–5990, 2007.
- 805 [141] Y. Cai, D. Newth, J. Finnigan, and D. Gunasekera, "A hybrid energy-economy model for global integrated assessment of climate  
806 change, carbon mitigation and energy transformation," *Appl. Energy*, vol. 148, pp. 381–395, Jun. 2015.
- 807 [142] V. Bosetti *et al.*, "Change Hybrid Model WITCH A World Induced Technical Change Hybrid Model Emanuele Massetti," *JSTOR*,  
808 2005.
- 809 [143] J.-C. Hourcade, M. Jaccard, C. Bataille, and F. Ghersi, "Hybrid Modeling: New Answers to Old Challenges Introduction to the  
810 Special Issue of The Energy Journal," *Energy J.*, vol. SI2006, no. 01, 2011.
- 811 [144] N. Shabani, S. Akhtari, and T. Sowlati, "Value chain optimization of forest biomass for bioenergy production: A review,"  
812 *Renewable and Sustainable Energy Reviews*, vol. 23, pp. 299–311, 2013.
- 813 [145] A. De Meyer, D. Cattrysse, J. Rasinmäki, and J. Van Orshoven, "Methods to optimise the design and management of biomass-for-  
814 bioenergy supply chains: A review," *Renewable and Sustainable Energy Reviews*, vol. 31, pp. 657–670, 2014.
- 815 [146] P. J. Ince *et al.*, "U.S. Forest Products Module: A Technical Document Supporting the Forest Service 2010 RPA Assessment,"  
816 2011.
- 817 [147] B. Peter and K. Niquidet, "Estimates of residual fibre supply and the impacts of new bioenergy capacity from a forest sector  
818 transportation model of the Canadian Prairie Provinces," *For. Policy Econ.*, vol. 69, pp. 62–72, 2016.
- 819 [148] K. Niquidet and D. Friesen, "Bioenergy potential from wood residuals in Alberta: a positive mathematical programming  
820 approach," *Can. J. For. Res.*, vol. 44, no. 12, pp. 1586–1594, 2014.
- 821 [149] C. S. Galik and R. C. Abt, "Sustainability guidelines and forest market response: an assessment of European Union pellet demand  
822 in the southeastern United States," *GCB Bioenergy*, vol. 8, no. 3, pp. 658–669, May 2016.
- 823 [150] G. S. Latta, J. S. Baker, and S. Ohrel, "A Land Use and Resource Allocation (LURA) modeling system for projecting localized  
824 forest CO<sub>2</sub> effects of alternative macroeconomic futures," *For. Policy Econ.*, vol. 87, no. October 2017, pp. 35–48, 2018.
- 825 [151] J. Perez-Garcia, L. A. Joyce, C. S. Binkley, and A. D. McGuire, "Economic impacts of climatic change on the global forest sector:  
826 An integrated ecological/economic assessment," *Crit. Rev. Environ. Sci. Technol.*, vol. 27, no. SPEC. ISS., pp. S123–S138, 1997.
- 827 [152] L. O. Eriksson *et al.*, "Climate change mitigation through increased wood use in the European construction sector-towards an  
828 integrated modelling framework," *Eur. J. For. Res.*, vol. 131, no. 1, pp. 131–144, 2012.
- 829 [153] S. Caurla, V. Bertrand, P. Delacote, and E. Le Cadre, "Heat or power: How to increase the use of energy wood at the lowest cost?,"

830 *Energy Econ.*, vol. 75, pp. 85–103, Sep. 2018.

831 [154] T. Beaussier, S. Cauria, V. Bellon-Maurel, and E. Loiseau, “Coupling economic models and environmental assessment methods to  
832 support regional policies: A critical review,” *J. Clean. Prod.*, vol. 216, pp. 408–421, Apr. 2019.

833 [155] L. Sievanen, L. M. Campbell, and H. M. Leslie, “Challenges to Interdisciplinary Research in Ecosystem-Based Management,”  
834 *Conserv. Biol.*, vol. 26, no. 2, pp. 315–323, 2012.

835 [156] L. M. Campbell, “Diversity Overcoming Obstacles to Interdisciplinary Research,” *Conserv. Biol.*, vol. 19, no. 2, pp. 574–577,  
836 2005.

837 [157] L. Tardieu and L. Tuffery, “From supply to demand factors: What are the determinants of attractiveness for outdoor recreation?,”  
838 *Ecol. Econ.*, vol. 161, pp. 163–175, 2019.

839 [158] G. S. Latta, J. S. Baker, and S. Ohrel, “A Land Use and Resource Allocation (LURA) modeling system for projecting localized  
840 forest CO<sub>2</sub> effects of alternative macroeconomic futures,” *For. Policy Econ.*, vol. 87, pp. 35–48, 2018.

841 [159] K. M. A. Chan, T. Satterfield, and J. Goldstein, “Rethinking ecosystem services to better address and navigate cultural values,”  
842 *Ecological Economics*, vol. 74. Elsevier, pp. 8–18, 01-Feb-2012.

843 [160] L. An, “Modeling human decisions in coupled human and natural systems : Review of agent-based models,” *Ecol. Modell.*, vol.  
844 229, pp. 25–36, 2012.

845 [161] S. Heckbert, T. Baynes, and A. Reeson, “Agent-based modeling in ecological economics,” *Ann. N. Y. Acad. Sci.*, vol. 1185, pp. 39–  
846 53, 2010.

847 [162] M. Janssen and E. Ostrom, “Empirically Based , Agent-based models,” *Ecol. Soc.*, vol. 11, no. 2, 2006.

848 [163] J. Pohjola, J. Laturi, J. Lintunen, and J. Uusivuori, “Immediate and long-run impacts of a forest carbon policy—A market-level  
849 assessment with heterogeneous forest owners,” *J. For. Econ.*, vol. 32, pp. 94–105, Aug. 2018.

850 [164] R. Yousefpour, A. L. D. Augustynczik, C. P. O. Reyer, P. Lasch-Born, F. Suckow, and M. Hanewinkel, “Realizing Mitigation  
851 Efficiency of European Commercial Forests by Climate Smart Forestry,” *Sci. Rep.*, vol. 8, no. 1, pp. 1–11, 2018.

852 [165] G. A. Mendoza and H. Martins, “Multi-criteria decision analysis in natural resource management: A critical review of methods and  
853 new modelling paradigms,” *Forest Ecology and Management*, vol. 230, no. 1–3. Elsevier, pp. 1–22, 15-Jul-2006.

854







