Integrating non-timber objectives into forest sector models: a review of recent advancements, technical innovations and current shortcomings

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Abstract

Forest sector models (FSM) encompass a set of partial equilibrium modelling frameworks originally conceived to perform projections of timber supply and forest inventories. Now commonly used for forest policy analysis, FSM have gradually integrated objectives other than timber production such as habitat conservation, carbon sequestration and bioenergy production. This paper gives an overview of non-timber objective (NTO) modelling in FSM through a systematic literature review followed by a more in-depth narrative review. In particular, we identify NTO that have been integrated into FSM, elicit technical innovations that have enabled it, and discuss current limitations to their integration. Results show that the study of NTO is a growing topic in FSM research, with bioenergy production and climate change mitigation as the most commonly studied NTO. However, there are discrepancies regarding the respective contributions of different families of models, and not all NTO have been integrated to the same degree. On the one hand, bioenergy production has been deeply integrated through marginal modifications of the market component of models. On the other hand, the modelling of carbon sequestration and habitat protection entails deeper changes, such as the addition of new resources to models, an increase in the complexity of the objective function and associated constraints, or the use of tools and models other than FSM. Critical steps for a better economic-environmental assessment of forest policies are to integrate more varied NTO into FSM and to allow NTO to enter the optimisation problem on the same level as timber production.

1. Introduction

Forest Sector Models (FSM) encompass a set of numerical simulation tools originally designed to carry out projections of timber supply, forest inventories and wood products trade and consumption over time. In particular, FSM are well-suited for scenario analysis, i.e. studies where the impacts of an exogenously introduced shock is assessed by comparing the model's outputs with a « Business As Usual » (BAU) case, where the shock is not introduced. Today, FSM are commonly used in the field of forest economics as tools for policy analysis, with a special focus on timber production and market dynamics. While timber production and wood products markets have stayed a core focus, FSM have also been used to investigate issues related to forest objectives other than timber production. In particular, topics such as habitat conservation, the production of wood-based bioenergy and climate change mitigation have become more and more prevalent in forest sector modelling research. While previous reviews have documented the history, evolution and theoretical foundations of forest sector models (e.g., Adams and Haynes, 2007; Latta, Sjolie and Solberg, 2013), to date, no detailed review analysis has been carried out on the integration of non-timber objectives within forest sector modelling literature. The objective of this paper is to fill this gap by investigating how and to what extent non-timber objectives have been integrated into FSM. In particular, we want to:

1. Identify which non-timber objectives have been studied, and give an overview of research questions investigated;
2. Identify which models and categories of models have been used to study non-timber objectives;
3. Elicit technical and methodological innovations that have allowed for the integration of non-timber objectives into FSM;
4. Describe current limitations to the integration of non-timber objectives into FSM.

The paper is structured as follows: in the next section, we give an overview of what FSM are and of the way they function. Such an introduction is necessary to understand the remainder of the article. Subsequently, we present the review methodology, the results of which are analysed in two sections: one dedicated to quantitative results from a systematic review while the other focuses on results from an in-depth narrative review. The main achievements in modelling non-timber objectives in FSM, as well as current limits, are discussed in the last section, where proposals for further investigation are made.

2. Forest sector models

FSM are bio-economic models of the forest sector where both biological resources as well as the economic system are represented. They are numerical simulation tools based on partial equilibrium, built to carry out projections of wood markets and forest inventories. They enable assessing the impacts of a user-defined shock on the forest sector, as well as to investigate the underlying market mechanics behind the observed changes. As a consequence, they are particularly well-suited to perform forest and climate policy analyses (Solberg, 1986; Latta, Sjolie and Solberg, 2013).

FSM are usually separated into two categories based on their handling of temporal issues (Sjølie *et al.*, 2015). On the one hand, static models solve market equilibria one at a time, and can be made dynamic by recursively updating the model's parameters. These models have short-sighted agents with adaptive anticipations, and are well-suited to carry out short to medium term projections. One the other hand, intertemporal models solve all equilibria at the same time. Such frameworks assume agents have perfect foresight, and are well-suited to carry out long-term projections (Latta, Sjolie and Solberg, 2013). In addition, FSM can be regional (e.g., Mustapha, 2016), national (e.g., Caurla *et al.*, 2010) or global (e.g., Buongiorno, 2014) in scope.

FSM can be thought of as being made of several components or modules (Northway, Bull and Nelson, 2013): (1) a timber supply module where forest resources can be represented with varying levels of details, (2) an industrial production component where primary products are converted into secondary and/or end-products, usually through input-output processes, (3) a demand component where demand functions for end-products are specified, and (4) a trade component, where various spatial formats can be employed (Adams and Haynes, 2007). In addition, some FSM contain a forest investment module where management decisions are endogenously determined, and some models such as the FASOM (e.g., Adams *et al.*, 1996) include the agricultural sector and land-use changes.

From a technical point of view, FSM are solved by optimising an objective function under a set of constraints usually forming a non-linear programming problem. Equilibrium is commonly found by maximising total economic surplus for the whole sector based on Samuelson's (1952) spatial price equilibrium framework, allowing for an endogenous determination of quantities and prices. More details on FSM can be found in Solberg (1986) and Buongiorno (1996) regarding early models and their uses, and Adams and Haynes (2007) and Latta, Sjolie and Solberg (2013) regarding the general evolution of modelling techniques.

3. Review methodology

Our review follows a two-step process. In a first step, we conduct a systematic literature review of studies using a FSM. Publications to be analysed are gathered using Scopus database. A first search query aims at retrieving publications based on historically significant FSM, using the models' names and abbreviations for them (e.g. "French Forest Sector Model", "FFSM"). The list of FSM included in the query is based on literature reviews on the development and history of FSM (Adams and Haynes, 2007; Latta, Sjolie and Solberg, 2013). A second search query uses keywords related to (1) common denominations used to describe FSM (e.g. "partial equilibrium model", "timber supply model", "spatial equilibrium model"), alongside (2) keywords related to the forest sector (e.g. "timber", "wood products", "forest sector") and economics (e.g. "market", "trade", "supply"). This allows us to retrieve publications where other FSM are used.

We then define a set of criteria to only keep publications where a FSM is actually used. We consider a FSM to be a model (1) rooted in economic theory, (2) representing the forest sector, which we define as forestry plus forest industries, (3) at the sector scale, and (4) at a temporal scale relevant to forest-related questions (for dynamic models). In addition, publications where a multi-sector model is used are only considered when the forest sector is the main focus of the paper. These criteria lead us to dismiss models such as forest growth and optimal forest management models (where the industry is not represented), models of the energy sector where non-energy uses of wood are not modelled, models at the individual owner/company scale, most biomass supply models (which usually operate at the yearly scale), and studies using multi-sector models not focusing on the forest sector.

This systematic search procedure yields a set of publications on which we perform a standard quantitative analysis (main scholars, main journals, dates of publication) in order to give a broad overview of field. In addition, based on titles, abstracts and keywords (and, when necessary, full-texts), we systematically identify (1) the research question, (2) the model used in the paper, and (3) if the focus of the paper is on a non-timber objective. This allows us to analyse the evolution of FSM studies' foci, to quantify the extent to which each model/type of model has contributed to the study of each non-timber objective, and to discuss which aspects of non-timber objectives are being investigated in terms of research question.

In a second step, we analyse in details how non-timber objectives are modelled in FSM studies. Since the literature available is very large for an in-depth analysis, we choose to conduct a narrative literature review where we focus on meaningful examples we believe are able to give valuable insights on the modelling of non-timber objectives. In particular, we identify and discuss the technical innovations that have enabled the integration of non-timber objectives into models, their limits, and compare innovations developed for different types of models. In order to document the evolution of modelling techniques over time, examples are mostly taken from FSM where sets of studies published several years apart are available. Examples from other models are presented when an approach we believe to be especially innovative is employed.

4. Systematic review analysis

General bibliometric analysis

The systematic review step yielded a total of 217 publications falling within the previously defined scope (c.f. Figure 1). Analysis of dates of publication shows that forest sector modelling is a growing research field, with 55% of papers published after 2010 and an increasing number of publications in each consecutive 5-years period from 1990 to 2018. More than half (53%) of the results have been published in one of 11 journals (Table 1), 4 of which are economics journals and account for 63 papers (29% of all results), while the 7 others are forestry journals and account for 53 papers (24% of all results). Two journals concentrate a high number of papers: *Forest Policy and Economics* (31 papers, 14%) and the *Journal of Forest Economics* (20 papers, 9%).

Journal	**Number of publications**	**Share (%) of all results**
Forest Policy And Economics	31	14%
Journal Of Forest Economics	20	9%
Forest Science	11	5%
Scandinavian Journal Of Forest Research	10	5%
Canadian Journal Of Forest Research	9	4%
Energy Policy	7	3%
Forest Products Journal	7	3%
Biomass And Bioenergy	6	3%
Canadian Journal Of Agricultural Economics	5	2%
Journal Of Forestry	5	2%
New Zealand Journal Of Forestry Science	5	2%
Others	101	47%

Table 1 – Distribution of reviewed papers among scientific journals

A total of 13 scholars have at least 10 publications – either as main author or as a co-author –, 5 of which have at least 20 publications (Table 2). Among the 217 publications, 9 are literature reviews, 10 are theory pieces about forest sector modelling, and 25 are presentations of a forest sector model. The other 173 are FSM studies, i.e. publications where a FSM is used to answer a thematic research question. We focus the rest of our analysis on these papers.

Author	**Number of publications**
Solberg, B.,	27
Buongiorno, J.,	25
Latta, G.S.,	22
Zhu, S.,	20
Adams, D.M.,	20
Kallio, A.M.I.,	15
Alig, R.J.,	15
Trømborg, E.,	12
Turner, J.A.,	12
McCarl, B.A.,	11
Sjølie, H.K.,	11
Caurla, S.,	10
Sohngen, B.,	10

Table 2 – Main scholars in FSM research, according to results from reviewed papers

Non-timber objectives in FSM studies: topics and temporal trends

We find that a significant proportion of the 173 FSM studies (66 papers, 38%) are entirely focused on timber production and wood products markets and do not investigate issues related to non-timber objectives. Focusing on the 107 (62%) remaining FSM studies, we identify 4 non-timber objectives as being the core focus of at least one study: the production of wood-based bioenergy (49 papers, 28%), climate change mitigation through carbon sequestration and/or substitution (32 papers, 18%), the conservation of forest resources and habitats (23 papers, 13%) and fire prevention (3 papers, 2%).

Some clear temporal trends can be identified regarding the investigation of non-timber objectives. While only 20% (50%) of FSM studies published in the period 2000-2004 (2005-2009) focus on a non-timber objective, this percentage increases to 84% (66%) in the periods 2010-2014 (2015-2018). The study of non-timber objectives is thus recent, and over time, the proportion of FSM studies focused only on timber production has decreased. In addition, there has been a shift with regards to which non-timber objectives are being investigated. In particular, the production of bioenergy seems to be a rather recent topic, with 90% of studies published since 2010. The same can be said, to a lesser extent, about climate change mitigation, with 63% of studies published since 2010. Conservation seems to be a slightly older focus of FSM research, with only 43% of studies published since 2010. In addition to being a recent topic, bioenergy production is also the most important non-timber focus in FSM research today, accounting for 49% (40%) of papers in the periods 2010-2014 (2015-2018). In comparison, FSM studies focused on conservation and climate change mitigation have never represented more than 20% of FSM studies published in any of the 5-years periods from 2000 to 2018.

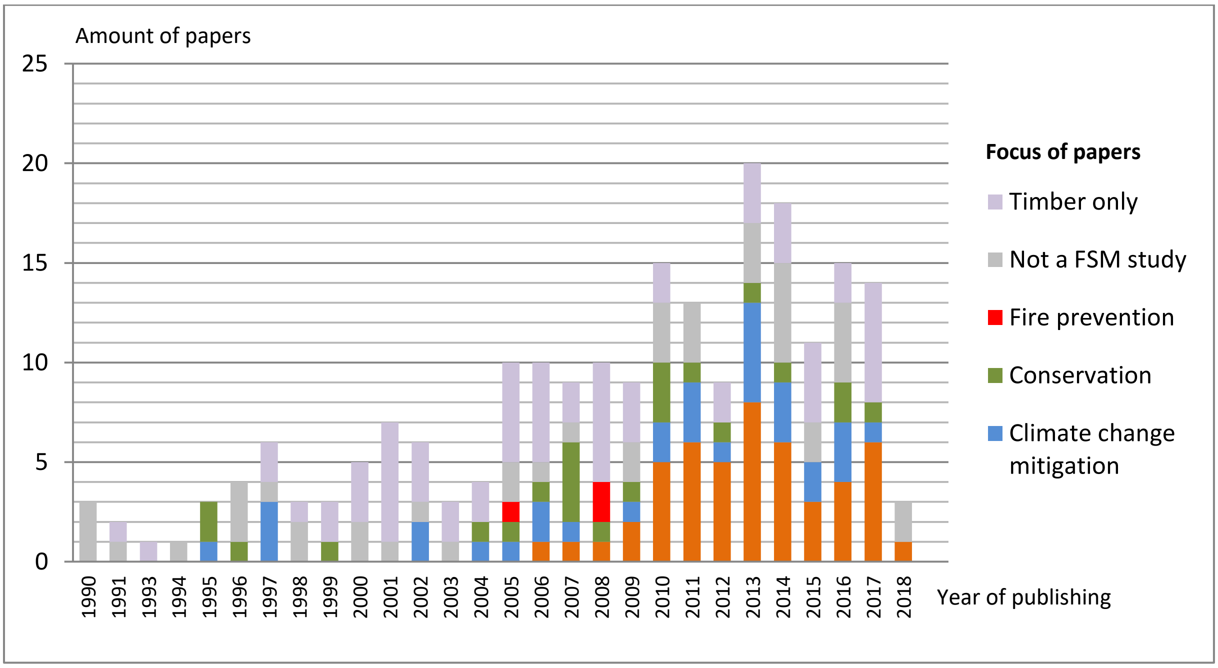


Figure 1 – Results from the systematic review analysis

Which model for which topic?

The 6 most widely used models are the Global Forest Products Model (GFPM, 32 papers), the Forest and Agriculture Sector Optimisation Model (FASOM, 16 papers), the Sub-Regional Timber Supply Model (SRTS, 13 papers), and the EFI-GTM and its national-level derivatives (SF-GTM and NTM), which together represent 20 papers. In addition, despite not always explicitly naming the models in use, 11 papers use modelling frameworks similar to B. Sohngen, Mendelsohn and Sedjo's (1999) Timber Supply Model (TSM), and another 11 papers use a framework similar to Stennes and Wilson's (2005) Spatial Price Equilibrium (SPE) model, which later gave the REPA-

FTM model described in Johnston and van Kooten (2014). Together, these models account for 103 (60%) of our results. 30 studies (18%) use a FSM occurring only once.

All models have not been used with the same purpose. On the one hand, studies using static-recursive models at the global and international primarily concern timber production and trade in wood-based products. Examples include the GFPM (24 out of 32), SPE (8 out of 11) and CGTM (4/6). On the other hand, studies where a static-recursive model with a local/regional focus is used tend to lean towards the study of bioenergy production. Such examples include EFI-GTM (global with a European focus) and its national derivatives SF-GTM (Finland) and NTM (Norway), with 10/20 studies focused on bioenergy, the Fibre Allocation Model (Canada, 3/3) and the SRTS (South-Eastern US, 7/13). Among the 4 studies using the FOHOW (Austria), 2 studies focus on bioenergy, while the 2 others use bioenergy policy as a strong assumption in scenario building. Similarly, among the 6 studies using the French Forest Sector Model (FFSM, France), 1 has bioenergy production as its main focus, while 2 others, despite focusing on climate change mitigation, include bioenergy policies in several scenarios. Intertemporal optimisation models are mostly used to investigate climate change mitigation: omitting models occurring only once, 21 (55%) studies have climate change as their main focus, against 10 for bioenergy and 7 for conservation. This rises to 11/16 (69%) for FASOM, the most represented intertemporal model.

Investigating non-timber objectives: a focus on research questions

Two different categories of research questions arise from our analysis: "*market projections*" and "*policy analyses*", both shown on Figure 2. On the one hand, *market projections* simulate an exogenous shock on the forest sector - usually a policy or a change of assumptions regarding the sector's behaviour – and assess its impacts on timber supply, forest inventories and industrial production over time: the focus is on the sector impacts of the studied shock/policy. On the other hand, *policy analyses* go further: while sector impacts of the simulated policy are still assessed, the focus is on discussing policy instruments themselves. As such, *policy analyses* usually simulate either several policy instruments (different approaches to the same issue) or several levels of the same policy (for quantitative instruments such as taxes) and discuss the features of each alternative: the focus is on policy design. The following subsections give a broad overview of the main research questions in FSM studies considering non-timber objectives.

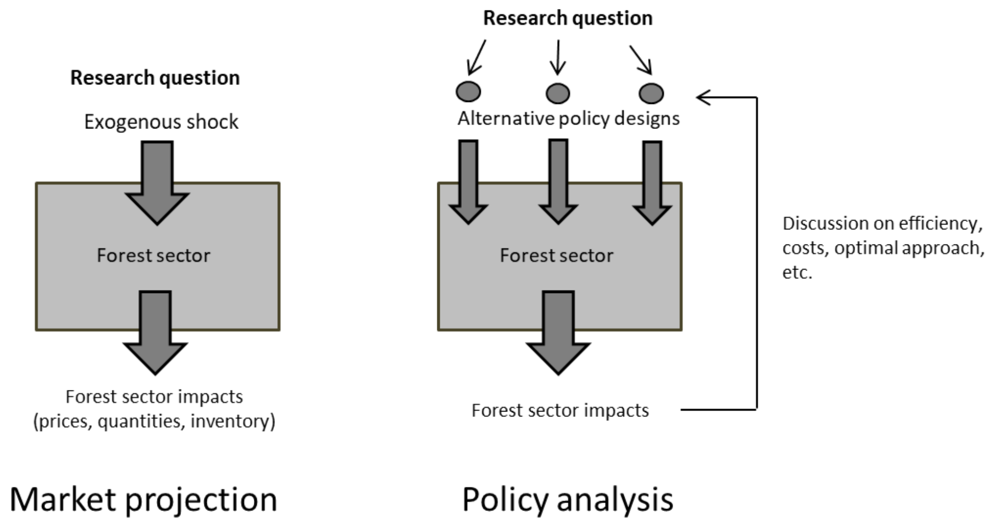


Figure 2 – Concepts of market projection *and* policy analysis *in FSM research*

Bioenergy

The main research question regarding bioenergy is to assess the consequences for the forest sector of an increased demand for/use of wood for energy production. However, not all studies assess the same impacts. 30 studies focus on economic impacts on the forest sector. Among these, 23 are *market projections*, most of which investigate the general use of woody biomass for energy (e.g., Buongiorno, Raunikar and Zhu, 2011) while others have a more specific focus such as heat and/or power generation (e.g., Trømborg and Solberg, 2010) or second-generation biofuels (e.g., Trømborg, F. Bolkesjø and Solberg, 2013; Kallio, Chudy and Solberg, 2018). Another 7 studies perform *policy analyses* and are concerned with the competitiveness of wood-based bioenergy under varying levels of subsidies and taxation (e.g., Trømborg, Bolkesjø and Solberg, 2007; Moiseyev, Solberg and Kallio, 2014). 10 studies assess impacts in terms of climate change mitigation and carbon balance, focusing either on sequestration in-situ (e.g., Sedjo and

Tian, 2012), or on emission reductions (e.g., Latta *et al.*, 2013; Galik *et al.*, 2015). Only one of these is a *policy analysis,* where a carbon tax policy and a bioenergy subsidy are compared (Sjølie *et al.*, 2010). The ecological impacts of bioenergy are addressed by 5 studies. Two of them are *market projections* focusing on land-use and land-use change (LULUC) aspects (Costanza *et al.*, 2017; Duden *et al.*, 2017), while another addresses the impacts of stump removal on biodiversity (Geijer *et al.*, 2014). The two remaining studies are *policy analyses* comparing sustainability guidelines for biomass supply, with criteria on LULUC and greenhouse gases (GHG) emissions (Böttcher *et al.*, 2013; Galik and Abt, 2016).

Finally, another important research question many studies were dealing with is the potential for various feedstocks to provide biomass. While most studies do address feedstocks, 10 of the papers reviewed put a particularly strong emphasis on assessing supply potential and costs for various feedstocks (e.g., Moiseyev *et al.*, 2011; Niquidet, Stennes and van Kooten, 2012; Martinkus *et al.*, 2017).

Conservation

The most common research question regarding conservation (13 papers) is to assess the economic impacts of decreasing harvest levels to preserve forest resources. In particular, eight studies focus on the removal of forestland from production through set-asides (e.g,. Bolkesjø, Trømborg and Solberg, 2005) and buffer-zones around streams (D.M. Adams and Latta, 2007a, 2007b). Most of these studies can be labelled as *market projections*. Two studies go further and perform *policy analyses* investigating the optimal allocation and opportunity costs of reserves (Kallio *et al.*, 2008; Hauer *et al.*, 2010) under several conservations targets/policy designs. Four of the papers we reviewed assess the sector impacts of (mostly trade) measures aiming at stopping illegal logging in tropical countries (Barbier *et al.*, 1995; Moiseyev *et al.*, 2010; Zhang *et al.*, 2016; Sun and Bogdanski, 2017). Another four investigate conservation in the front of other land uses and land use changes: two of these focus on Europe and wetland conservation (Schleupner and Schneider, 2010, 2013), while two others are dedicated to tropical cases (Merry *et al.*, 2009; A. Mosnier *et al.*, 2014). All of these test alternative policy designs, often with several levels or targets, and can be labelled as *policy analyses*. Finally, one study focuses on the opportunity costs of a forest certification scheme (Busby, Montgomery and Latta, 2007), while the last study investigates a model's assumptions on forest owners' heterogeneity in preferences for non-timber amenities (Pattanayak *et al.*, 2004).

Climate Change mitigation

Climate change mitigation as a non-timber objective has been investigated in two different ways. On the one hand, 26 out of 32 reviewed studies assess the potential of different mitigation strategies and mostly perform *policy analyses*. The main focus is on market instruments, especially the creation of carbon markets where a payment/tax for carbon sequestration/emissions is put into place. While most studies assess the general implications of such carbon policies (e.g., Buongiorno and Zhu, 2013; Latta *et al.*, 2016), some others deal with specific features such as the incorporation of albedo (Sjølie, Latta and Solberg, 2013b), dual discounting (Sjølie, Latta and Solberg, 2013a) or the comparison of mandatory versus voluntary schemes (Latta *et al.*, 2011). Two studies focus on comparing a substitution policy to a sequestration policy (Lecocq *et al.*, 2011; Caurla, Delacote, Lecocq, Barthès, *et al.*, 2013). In addition to market instruments, 7 papers focus on mitigation strategies based on land use policy and/or direct changes in forest management (e.g., Alig and Bair, 2006; Im, Adams and Latta, 2010), 2 papers combine land use/management tools and market instruments (Sathaye *et al.*, 2005; Alig *et al.*, 2010) and 3 papers investigate the mitigation potential of structural changes in specific segments of the forest sector: construction (Eriksson *et al.*, 2012; Nepal *et al.*, 2016) and transport (Tromborg *et al.*, 2009).

On the other hand, 6 studies in our review perform *market projections* to assess the impacts of climate change on the forest sector. While other studies with the same research question were classified as "timber only", we chose to include these specific 6 studies as focusing on climate change mitigation as a non-timber objective because they include an assessment of impacts on the carbon balance of the forest sector. On the contrary, studies considered as "timber-only" only assess the economic impacts of climate change.

Fire prevention

Three papers we reviewed have fire prevention as the main non-timber objective studied, and all focus on assessing the impacts of mechanical treatments to reduce fire frequency. Ince *et al.* (2008) compare two different management strategies for fire prevention (even-aged and uneven-aged thinnings), while both Prestemon, Abt and Huggett (2008) and Adams and Latta (2005) assess the impacts of government-financed programmes with different designs and varying levels of subsidies.

5. Narrative review analysis

The narrative review focuses on the modelling of non-timber objectives from a more technical point of view. We centre our analysis around three examples of non-timber objective-related questions addressed by FSM research, chosen from results of the systematic review step: (1) the modelling of reserves and set-asides, identified as one of the main research questions on forest conservation as a non-timber objective; (2) the modelling of the bioenergy value chain, from feedstocks to end-use products, which has been a necessary development for all models used in papers focusing on bioenergy; (3) the modelling of market instruments for climate change mitigation, which the systematic review revealed to be the most commonly studied mitigation instrument. Examples will be taken primarily from papers from the systematic review, but a small number of other examples will also be discussed.

Forest conservation through reserves and set-asides

The modelling of reserves and set-asides in FSM entails the *ex-ante* identification of areas to conserve. Two cases should be distinguished: either the study focuses on (1) investigating already-existing reserves, or (2) on the impacts of establishing new reserves. While the former relies on already existing data to identify conserved areas, the latter requires a way to assess the suitability of forests for conservation. However, in early studies such as Perez-Garcia (1995) and B. Sohngen, Mendelsohn and Sedjo (1999), newly established set-asides are not targeted, and concern a fixed quantity/proportion of all forests in a specific region: areas suitable for conservation are not identified, and, among these, there is no choice regarding where conservation will actually be applied. This shortcoming was addressed by two waves of innovation.

1. A first innovation was to allow models to identify areas relevant for conservation using one or several sets of criteria. In a group of studies using static-recursive models focused on Europe, reserves target mature forests only, which are identified using a structural criterion: forest density (e.g., Bolkesjø, Trømborg and Solberg, 2005; Hänninen and Kallio, 2007), while in two studies using intertemporal models of the US Pacific North-West region (PNWM), reserves are buffer-zones of varying width around streams, which are thus defined using a geographical criterion (D.M. Adams and Latta, 2007a, 2007b). Using ecological data, Kallio *et al.* (2008) go even further and build habitat quality indices from which the amount of forest land suitable for conservation in each region of Finland is identified and used as input in the FSM.
2. The second innovation was to make the choice of areas to be preserved endogenous. This new paradigm is easily observable when comparing Hänninen and Kallio (2007) and Kallio *et al.* (2008). In the former, a fixed percentage of all forests deemed suitable is removed from production. In the latter, a new agent whose is introduced, whose aim is to distribute a conservation target among all forests identified as having a high habitat quality. This translates as an additional constraint on the optimisation problem: conservation becomes a decision variable. The use of such constraints can also be seen in Hauer *et al.* (2010), Montgomery, Latta and Adams (2006) and Schleupner and Schneider (2010, 2013).

Both in the case of already-existing and newly established reserves, another innovation has greatly benefited to FSM research on conservation: the increasing use of spatially explicit tools.

All FSM are to some extent spatialised, and in the most basic case, regions with separate inventories and forest industries are represented. In the SF-GTM for instance (Hänninen and Kallio, 2007), these correspond to the Finnish Forestry Centres, and in the EUFASOM (Schleupner and Schneider, 2010), to European countries. However, many studies present a finer level of spatial detail, and usually rely on one of two solutions: (1) the use of an FSM built with more spatial details than in the basic case described above, or (2) a linkage between an FSM with basic spatial features and a more spatially detailed tool, usually GIS based. In both cases, it entails the use of spatially explicit data. When studying newly established reserves, the use of spatial tools has enabled the investigation of optimal reserve allocation, which was not possible without those tools, while in the case of already existing reserves, spatial tools were a requirement. Table 3 shows the different cases occurring.

	Supplementary spatialised tool	**Spatialised FSM**
Optimal allocation of newly established reserves	- Kallio *et al.*, 2008 - Schleupner and Schneider, 2013	-Montgomery, Latta and Adams, 2006 - Hauer *et al.*, 2010)
Location of already existing reserves	- Schleupner and Schneider, 2010, 2013	-D.M. Adams and Latta, 2007a,b - Merry *et al.*, 2009 - A Mosnier *et al.*, 2014)

Table 3 – The use of spatial tools in conservation FSM research

While these tools and approaches have mostly been developed to study fixed reserves where a permanent area is removed from production (Hänninen and Kallio, 2007; Merry *et al.*, 2009), some studies propose a dynamic approach to conservation, where the location of preserved areas can vary over time: conserved areas are not chosen but emerge from the management decisions taken by the model's agents (e.g., Montgomery, Latta and Adams, 2006; Hauer *et al.*, 2010). We consider this alternative approach to the design of reserves to be an innovation *per se*. Its significance is highlighted by Montgomery, Latta and Adams (2006), where the new approach is compared to a scenario with the more common fixed reserves.

Regarding the implications of conservation, a majority of FSM studies only assess economic consequences on the forest sector, that is to say, impacts on products prices and quantities produced and traded. Impacts on habitat quality, biodiversity and non-timber amenities are often cited as benefits that conservation policies can help secure, but they are rarely assessed. Kallio et al. (2008) for instance suggests that if benefits derived from forest conservation were actually evaluated, they could alleviate the estimated welfare losses. Some attempts have been made at assessing the ecological impacts of reserves. In Pattanayak *et al.*, (2004) and Hauer *et al.* (2010), *ex-post* analyses on habitat suitability for local species, and bird abundance respectively, are performed. In both cases, the FSM are not able to perform the analysis themselves, and need to be supplemented by other models. The impacts of reserves in terms of land use changes have also been assessed, focusing on tradeoffs between forestry, agriculture and wetland conservation in Schleupner and Schneider (2010, 2013) and deforestation in the Congo Basin in the wake of REDD+ programmes in Mosnier *et al.* (2014). For both studies, the study of land use changes is made possible by the use of multi-sector models: EUFASOM (forest and agriculture) for the former, GLOBIOM (forest, agriculture and energy) for the latter.

Climate change mitigation

Carbon accounting in forest sector models

The ability of FSM to investigate climate change mitigation strategies relies heavily on the development of some form of carbon accounting modules. We discuss their development focusing on (1) forest carbon accounting (i.e., carbon in forest pools and associated fluxes, c.f. Figure 3) and (2) sector carbon accounting (i.e. carbon in forest products pools, associated fluxes and net gains from substitution effects).

The main pools included in accounting forest carbon accounting modules are live and dead tree biomass, sometimes disaggregated into more compartments, understory biomass, carbon in residues and on the forest floor and, sometimes, forest soils. Forest carbon accounting has mostly been developed in intertemporal models such as FASOM-GHG (e.g., Adams *et al.*, 2011) or NorFor (Sjølie *et al.*, 2011), but some static-models such as FFSM (Lobianco *et al.*, 2016) and SRTS (Abt, Abt and Galik, 2012) also contain a carbon accounting module. Forest carbon accounting relies on the presence of a sufficient level of detail in forest resources description. The static-recursive FFSM is a very good illustration of this phenomenon: the early FFSM 1.0 version only had regionally aggregated data on resources, and no to a very rough form of overall forest carbon accounting (Lecocq *et al.*, 2011), while the more spatially disaggregated FFSM++ version has spatially explicit, strata-level data on resources and a detailed carbon accounting module with several pools (Lobianco *et al.*, 2016). Similarly, the regional SRTS and most intertemporal models include strata/plot level data on forest resources. Other static-recursive models either do not perform forest carbon accounting, or rely on linkages to other models (e.g., Kallio, Salminen and Sievänen, 2013).

Full sector accounting has been developed for a few models only, such as FFSM++ (Lobianco *et al.*, 2016), FASOM-GHG (e.g., Adams *et al.*, 2011) , NorFor (Sjølie *et al.*, 2011) and PNWM (Im, Adams and Latta, 2010). Such frameworks rely on the existence of forest carbon accounting, from which fluxes to forest products pools are originating. Fluxes from harvests, transport and processing are included, and end-of-life destinations for wood products are modelled. Solutions commonly found are decay over time, indefinite sequestration in products and/or landfills, recycling and combustion. Net gains from energy or material substitution are modelled using substitution coefficients and assumptions on substituted materials/fuels. Most studies consider bioenergy to be carbon neutral at combustion, meaning that no CO2 is emitted when fuels are consumed. Emissions of other GHG gases at combustion, and carbon emissions during fuel production are usually included. Only a few papers (e.g., Sjølie and Solberg, 2011; Caurla, Delacote, Lecocq and Barkaoui, 2013; Kallio, Salminen and Sievänen, 2016) discuss the assumption that forest biomass is carbon neutral, even though such a claim heavily depends on the sequestration efficiency of the forest and its future evolution (Valade *et al.*, 2017).

While not having developed such sector-accounting modules *per se*, many models are able to estimate net gains from substitution without needing to estimate pools in forests or wood products. This point is discussed in the section on bioenergy regarding energy substitution. Regarding material substitution, the EFI-GTM, which doesn't include a sector accounting module either, has been linked to a substitution model to account for material substitution effects in a study focused on wood construction (Eriksson *et al.*, 2012).

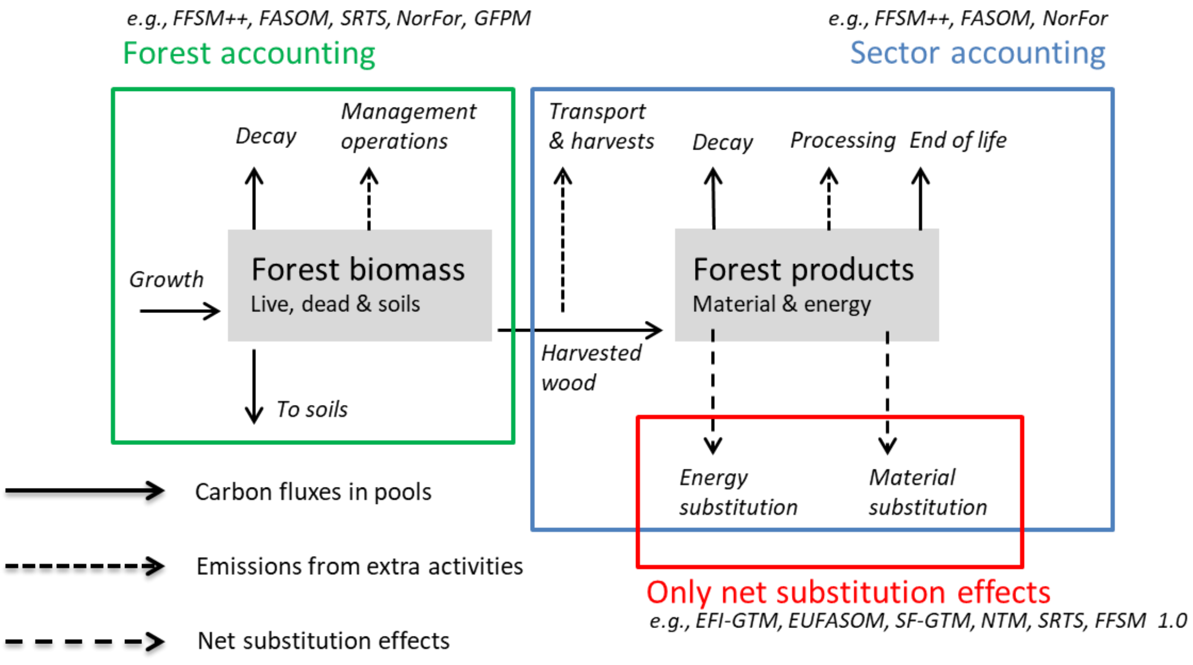


Figure 3 – General overview of carbon accounting techniques in FSM

<u>Modelling of market-based mitigation instruments</u>

Two different kinds of market-based mitigation instruments have been modelled using FSM: (1) taxes on GHG emissions and (2) carbon offset payments. They refer to two different forest-based strategies to mitigate climate change: substitution and sequestration. Taxes on GHG emissions are a tool pertaining to the substitution strategy, aiming for reduced net emissions of GHG when substituting biomass for fossil-based alternatives. Such taxes are usually modelled as an exogenous increase in price/costs for fossil fuels, which impacts agents' behaviours and, consequently, the models' solution. In EFI-GTM, SF-GTM and EUFASOM, where fossil-based energies are modelled explicitly, the tax increases costs for fossil inputs, making biomass-based solutions more price-competitive as a result (e.g., Moiseyev, Solberg and Kallio, 2013). On the contrary, in models where only biomass-based energy is modelled, taxes on GHG emissions indirectly increase the demand for bioenergy through cross-price elasticities (e.g., Caurla, Delacote, Lecocq and Barkaoui, 2013) or upwards shifts of demand curves (e.g., Sjølie *et al.*, 2010).

On the other hand, offset payments are a tool pertaining to the sequestration strategy, which aims at increasing the amount of carbon stored in forest biomass and soils. Their modelling entails the addition of sequestered carbon as an additional product for which forest owners are remunerated at an exogenously defined price. Payments are usually symmetrical, meaning that negative payments take place when pools decrease. From a technical point of view, the difference between the carbon pool and a reference level multiplied by the carbon price is added as an extra term to the model's objective function or to the timber supply function, which changes the model's solution. Details are given in Im, Adams and Latta (2007) and Sjolie, Latta and Solberg (2013) in the case of an intertemporal model, and in Lecocq *et al.* (2011) and Buongiorno and Zhu (2013) in the static-recursive case. An important point in the modelling of offset payments is the choice of the reference level. While most studies use sequestration in the base model run (without offset scheme) as a reference, some other solutions include the use of regional averages as a lower threshold (Latta *et al.*, 2016), or definitions based on political instruments such as the Kyoto protocol, which imposes a cap on sequestration offsets (Sjølie, Latta and Solberg, 2014; Kallio, Salminen and Sievänen, 2016). Some other variations found include: the application of payments to fluxes other than in-situ sequestration (e.g., Lee, McCarl and Gillig, 2005; Sjolie, Latta and Solberg, 2013) the incorporation of a second discount rate specific to carbon payments (Sjølie, Latta and Solberg, 2013a) or an additional payment linked to radiative albedo forcing converted to C02 equivalents (Sjølie, Latta and Solberg, 2013b).

The choice of instruments heavily conditions the research question that can be investigated. Intertemporal models are mostly used to investigate sequestration, offset payments and mitigation from forest management and land-use, while static-models have contributed more to the study of energy substitution and taxes on emissions. Even though most of the publications reviewed focus on one aspect only, some assessed the two strategies in front of one another, for the specific cases of France (Lecocq *et al.*, 2011; Caurla, Delacote, Lecocq, Barthès, *et al.*, 2013) and Finland (Kallio, Salminen and Sievänen, 2013, 2016). These studies demonstrate that substitution strategies may *in fine* be less effective than sequestration strategies because they induce a reduction in forest carbon sequestration that avoided emissions cannot offset. However, tradeoffs are multi-faceted: sequestration policies may be less politically acceptable because of their negative impacts on consumer surpluses and, even though forest growth alone could meet emission reduction targets, other instruments are necessary since sequestration offsets may be limited by caps introduced in the policy.

In addition to market instruments, carbon has also been integrated to the optimisation problem as a constraint on the objective function. For instance Im, Adams and Latta (2010) impose minimum forest flux targets, similarly to constraints imposed on reserve allocation in Kallio *et al.* (2008). This approach is however less common than the use of carbon prices and market-based instruments.

Modelling of bioenergy production

Advancements in the modelling of bioenergy markets are discussed in three points. A first innovation is seen in the disaggregation of products and technologies represented in FSM. A second concerns the way bioenergy demand is modelled and driven, while the last innovation concerns the addition of the climate impacts of bioenergy and competition with fossil fuels.

Disaggregation of the value chain

On the supply side, the disaggregation of products is seen in the many feedstocks represented, which are common to many FSM (see Figure 4). (1) The roundwood feedstock is derived directly from timber supply, which is either represented as a price-elastic supply function, or is an implicit result of endogenous management decisions. Some models have a dedicated roundwood fuelwood category (e.g., Raunikar *et al.*, 2010; Lauri, Kallio and Schneider, 2012; Johnston and van Kooten, 2016), and many frameworks allow pulpwood and/or sawlogs to be diverted to energy uses when it becomes economically viable to do so. Examples include the "*cascading substitution*" used in later versions of the USFPM/GFPM, where all higher-value fiber can be used for energy (Zhang, Gilless and Stewart, 2014). In the SRTS, a very different solution is found: bioenergy demand must first be met by harvest residues: the unmet demand is then used to shift pulpwood demand, which can then be diverted to energy uses (Abt, Abt and Galik, 2012). (2) The harvest residue feedstock is also commonly found, and comprises lower-value remnants such as tree tops and branches. Potential supply is usually represented as a share of harvest volumes, and a marginal cost (supply) function is defined to represent the extra costs when retrieving residues. Most models determine supply of harvest residues during the model run where a shock is introduced, while in the SRTS, it is estimated *ex-ante,* in the base model run (Abt, Abt and Galik, 2012). A notable exception to including harvest residues is the REPA-FTM, where they are omitted because of their low economic viability (Johnston and van Kooten, 2016). (3) The industrial residues feedstock is present in all models where processing activities (such as plywood or sawnwood production) are modelled, and encompass sawmill chips, dust and bark. Industrial residues are represented as a by-product of input-output processes. In addition to constituting bioenergy feedstocks, industrial residues can also be used as an input for manufacturing activities using lower-grades materials, such as the production of pulp, paper or particleboard. Hence, in most models, the bioenergy sector competes with other segments of the forest sector for this feedstock. (4) Finally, some models diversify feedstocks even more. This includes agricultural residues in FASOM-GHG (Latta *et al.*, 2013), short-rotation coppices in

GFPM (Zhang, Gilless and Stewart, 2014) or recycled wood in EUFASOM (Lauri, Kallio and Schneider, 2012).

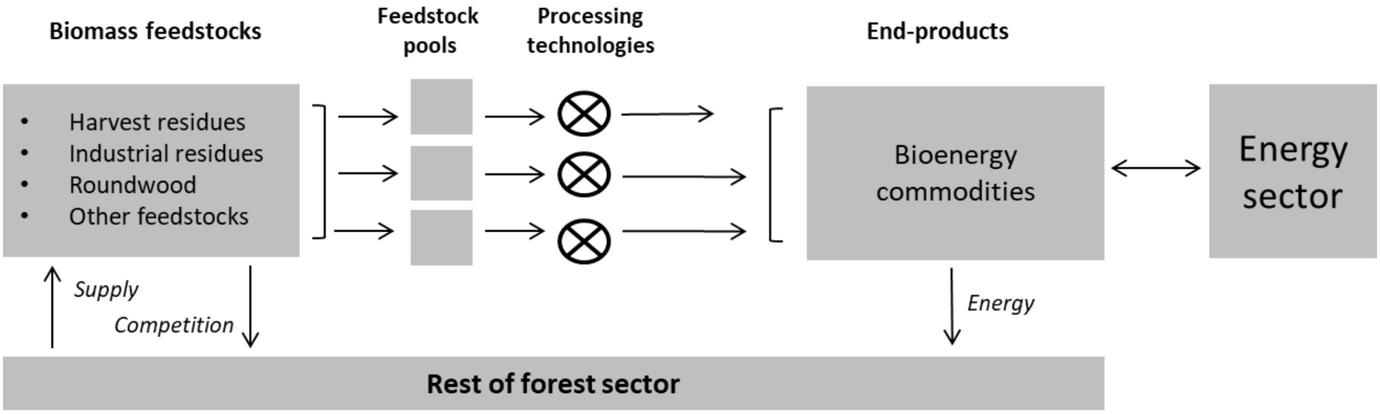


Figure 4 – Modelling of the bioenergy value chain in FSM

On the demand side, the disaggregation of products is even more visible, and models tend to multiply the amount of bioenergy commodities represented. In early model versions, bioenergy commodities were not explicitly modelled. Rather, fuelwood was modelled as a broad category of end-product, and not converted into energy. Examples include the GFPM in Ince *et al.* (2011) and the EFI-GTM in Moiseyev *et al.* (2011). Models were later refined with the addition of bioenergy commodities, sometimes disaggregated into several end-products. Later versions of the EFI-GTM (Moiseyev, Solberg and Kallio 2013) include both heat and electricity as energy commodities, while the GFPM (Zhang, Gilless and Stewart, 2014) also models bioethanol markets. For other models, the choice was made to focus on one particular bioenergy commodity, and to model it with more details. Such an example is the NTM (e.g., Bolkesjø, Trømborg and Solberg, 2006), focused on the bioheat market, and the NFSM (Mustapha *et al.*, 2017), built to study biofuel markets in Scandinavia. These innovations go hand in hand with the development of ways to represent the conversion of biomass into bioenergy commodities. All models reviewed use input-output processes to represent the conversion of biomass into bioenergy commodities, with coefficients indicating the quantity of inputs necessary to produce one unit of energy/biofuel. Some models, such as the GFPM (Zhang, Gilless and Stewart, 2014), use one conversion process per commodity, while others, such as the NTM (Bolkesjø, Trømborg and Solberg, 2006), EFI-GTM (Kallio, Chudy and Solberg, 2018) and EUFASOM (Lauri, Kallio and Schneider, 2012), enable the production of commodities from several competing technologies.

Biomass from various feedstocks can be found under several forms, such as chips, pellets or firewood, with different characteristics that condition their uses. Many FSM where several conversion technologies are modelled introduce such distinctions through the construction of feedstock pools dedicated to different technologies. In the NTM, biomass from all feedstocks is partitioned into chips, pellets and firewood categories (Bolkesjø, Trømborg and Solberg, 2006), and in the fibre allocation model of the Canadian provinces, residues are separated into hog fuel, chips and whitewood residuals (Peter and Niquidet, 2016). The GFPM and the EUFASOM distinguish between several biomass grades within the same feedstock: industrial fibre residues and industrial fuel residues for the former (Zhang, Gilless and Stewart, 2014), and two grades of recycled wood for the latter (Lauri, Kallio and Schneider, 2012). Such frameworks enable studying the sensitivity of the sector to potential feedstock restrictions.

Modelling bioenergy demand and model drivers

While models do not differ much in the way they model energy products themselves, choices regarding the modelling of demand for bioenergy commodities vary more widely. These choices condition the research questions that can be investigated using the models, and three main approaches can be identified. (1) Some models use price elastic demand functions, similar to those commonly used for material wood products. In this case, both produced quantities and prices are defined endogenously. Examples include the GFPM (Zhang, Gilless and Stewart, 2014), REPA-FTM (Johnston and van Kooten, 2016) and FFSM (Caurla, Delacote, Lecocq and Barkaoui, 2013). (2) Others use horizontal demand curves, based on the assumption that bioenergy commodities will replace fossil fuels until marginal costs equal the exogenously fixed price. In this case, prices are exogenous but quantities endogenous. Such a framework is used in the NTM

(Bolkesjø, Trømborg and Solberg, 2006) and in the EFI-GTM for fuelwood (Moiseyev *et al.*, 2011). (3) Finally, some studies elected to have an exogenously fixed level of demand constraining energy production. In this case, the model is limited to endogenously determining the allocation of production among different regions/technologies. Examples include biofuels in NFSM (Mustapha *et al.*, 2017) and heat and power in EFI-GTM (Moiseyev, Solberg and Kallio, 2013) and EUFASOM (Lauri, Kallio and Schneider, 2012).

Modelling the climate impacts of bioenergy: fossil fuels and avoided emissions

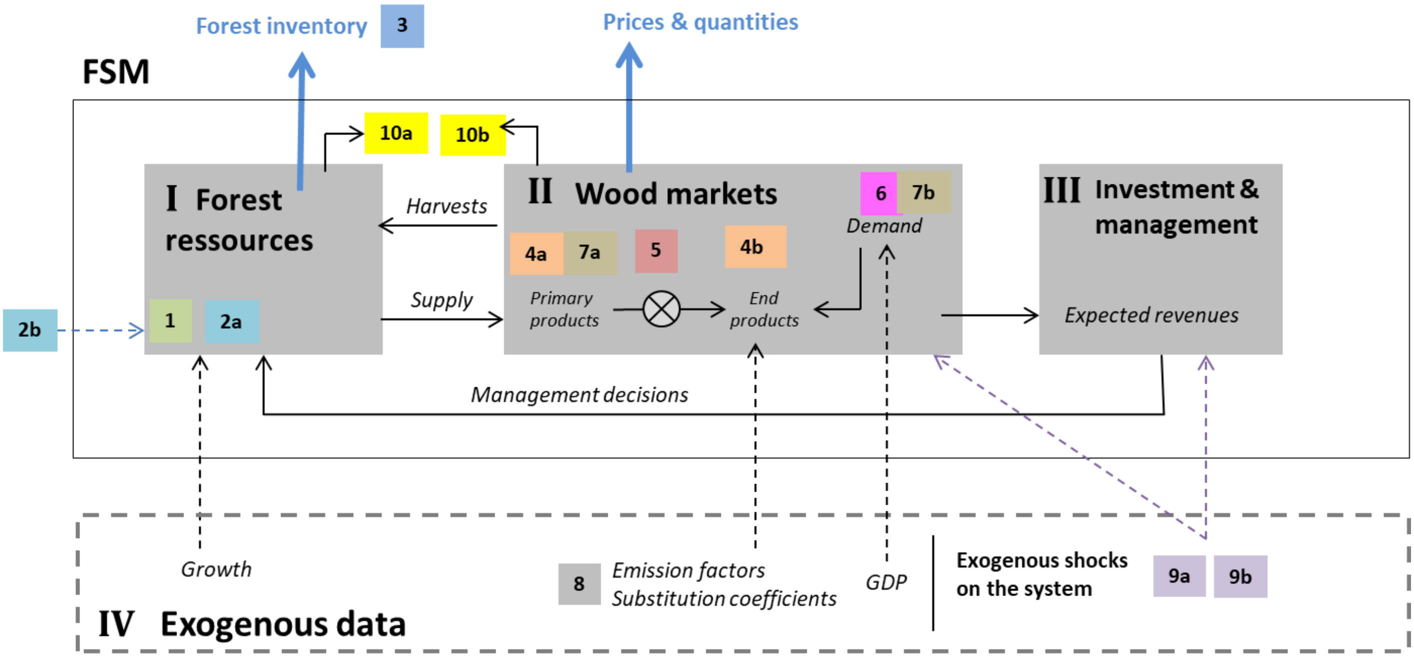
One final innovation in the modelling of bioenergy is the development of ways to represent its climate benefits, especially substitution effects that take place when fossil fuels are displaced. In particular, several different approaches to including competition between bioenergy and fossil energy have been developed. On the one hand, some models include competition between bioenergy and fossil fuels indirectly, at the demand level. When using horizontal demand curves, the production of bioenergy depends on exogenously fixed prices for general energy, including fossil fuels: changes in the fixed energy price can emulate price-based competition between bioenergy and fossil energy (e.g., NTM in Bolkesjø, Trømborg and Solberg, 2006). When using price-elastic demand curves, cross-price elasticities for fossil fuels can be introduced, which enables more precise price-based interactions (e.g., FFSM in Caurla, Delacote, Lecocq, Barthès, *et al.*, 2013). One the other hand, other models opt for modelling a direct competition between bioenergy and fossil fuels by introducing fossil fuels as inputs for fossil-fuelled and co-fired technologies alongside biomass-fired technologies in the input-output production processes. Combined with fixed levels of production, this approach enables to study the allocation of the energy mix between alternative energy sources (e.g., EUFASOM in Lauri, Kallio and Schneider, 2012).

Another trend going in the same direction is the development of methods to calculate the substitution effect taking place when bioenergy is used rather than fossil fuels, i.e., to calculate avoided GHG emissions. A common methodology is to introduce emission factors for each conversion technology, where emissions both at combustion and over the production process are taken into account. When fossil-based technologies are represented, a direct comparison of emissions can be made. When only biomass-fired technologies are modelled, an additional assumption must be made regarding (1) the fossil fuels which is substituted and (2) the substitution coefficients used. Sjølie *et al.* (2010) use NTM and give a good example of the former, while Moiseyev, Solberg and Kallio (2013, 2014) illustrate the latter using EFI-GTM. The calculation of avoided emissions allow models to be driven by carbon prices, which consequently enables a better investigation of the mitigation potential of bioenergy as well as of the interlinkages between climate and bioenergy policies. In cases where a forest carbon accounting is also present, it enables investigating the net climate impacts of bioenergy and the potential conflicts between sequestration and substitution policies.

6. Discussion and future prospects

Different categories of modelling innovations

Our case studies reveal that several waves of innovations have allowed for the modelling of non-timber objectives. These vary regarding (1) the extent to which they modify the models and (2) the components of the model they concern, as shown on Figure 5. Most innovations target the market component of models. These primarily consist of increases in complexity of the value chain with additions of products, technology inputs and transformation processes (4a, 4b, 5, 7a). Such technical innovations are marginal since they modify neither the model's structure nor its general functioning. 6 and 7b introduce new specifications for demand equations and, similarly, the introduction of market instruments related to carbon management (9a and 9b) are usually materialised as new terms in the objective function, which bear on agents' utility or profits. Such innovations bring a deeper change and modify agents' behaviours, the model's solution and enable the user to perform new types of analyses where energy or climate policies are used to drive the model. They are more advanced and can be labelled as methodological innovations. Innovations 8, 10a and 10b result in the addition of carbon as a new resource as well as of a new functionality in carbon accounting. Moreover, these innovations are crucial to the development of market-based climate instruments (9a and 9b). They add new components to FSM and open doors for a novel uses: they are both structural and supporting innovations. Only three innovations occur at the level of the forest resources component, and all increase the complexity in resource description (1, 2a and 2b). Developing a spatial format for forest inventory can be done both inside the model (2a), which is a structural change, while 2b requires the use of an extra-model tool. On the other hand, improving the location of areas for conservation does not change the way resources are represented, but is a methodological innovation where new constraints are imposed on the optimisation problem. Finally, the assessment of ecological consequences (3) almost represents a change of paradigm in the way FSM are used, since it adds a new dimension to the analysis besides the economic analysis usually allowed. However, this often relies on the use of extra-model tools using the FSM's outputs as inputs. It can be considered as a theoretical innovation.



Innovations considered are: **(1)** Targeted set-asides for conservation, **(2)** The use of spatially explicit tools **(a)** inside or **(b)** outside the model, **(3)** Assessment of ecological impacts, **(4)** Disaggregation of products, **(5)** Disaggregation of processing technologies, **(6)** New specifications for demand functions, **(7)** The inclusion of fossil fuels **(a)** as technology inputs or **(b)** in demand functions, **(8)** The assessment of avoided emissions, **(9)** Market-based instruments for carbon management as **(a)** taxes on emissions or **(b)** sequestration payments, **(10)** Carbon accounting in **(a)** forests and **(b)** wood products.

Figure 5 – Integration of non-timber objectives into FSM: a general overview of modelling innovations

Current limits and future prospects

The innovations discussed all along this review have allowed for new ways to use FSM and are the main reason why the investigation of non-timber objectives has gradually become a central topic, with a high amount of publications despite a significant number of papers still solely considering timber production. Even though the time seems ripe for the study of non-timber objectives, our results reveal that only four have been addressed: conservation, climate change mitigation, bioenergy production and fire prevention. Many ecosystem services provided by forests, such as recreation and erosion control, have not been addressed. In addition, studies are unevenly distributed among the non-timber objectives identified, and there exist discrepancies regarding the respective contributions of various families of FSM to the field.

As pointed out on several occasions, this is usually related to the technical limitations and underlying assumptions behind each model, which in turn influences the research questions investigated. The integration of bioenergy production only requires the addition of new market segments, which does not require fundamental changes in the models' structure. The modelling of carbon sequestration requires more complex changes, but relies primarily on forest inventory data, which is already present in most FSM. Contrary to carbon sequestration, which can potentially happen on any forest land and be remunerated regardless of location, the spatial component of most other ecosystem services is stronger and entails the use of a level of spatial detail most FSM have not yet achieved. Such a limit is observable in conservation studies, where exogenous data and extra-model tools regularly need to be employed.

Finally, it is clear from our results that not all non-timber objectives benefit from the same level of integration. Timber production, for instance, is integrated into FSM as a perfect loop: agents' behaviours determine the output (timber production), which in turn influences agents' behaviours through the objective function (figure 6). Bioenergy production follows the same pattern. On the other hand, conservation reserves are commonly treated as exogenous constraints on the optimisation problem. They do not enter the objective function proper and, in rare cases where ecological impacts are assessed, they are only so as an output. Sequestered carbon is in an intermediate situation: most models include it as a biophysical output; some allow feedback by monetizing it.

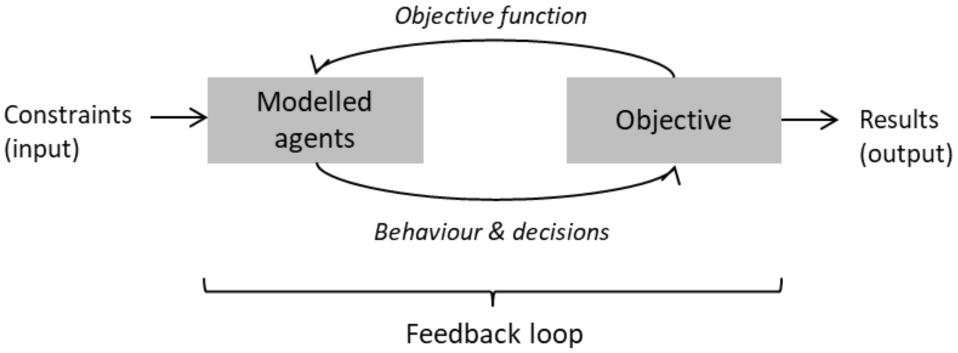


Figure 6 – Integration of non-timber objectives into FSM through feedback loops

The integration of non-timber objectives into FSM is crucial to ensure better economic-environmental assessment of forest policies. Interesting developments for further study of non-timber objectives would be:

1. The addition of other ecosystem services such as recreation to models.
2. A deeper integration through the development of feedback loops where non-timber objectives are allowed to enter the optimisation problem at parity with timber production.
3. Allowing non-timber objectives to be integrated without needing to be monetised. Such an evolution would require a change in optimisation techniques, since several variables of different nature would need to be optimised simultaneously. Currently, only economic surplus is maximised, while other potential biophysical variables are downgraded to secondary constraints.

Our analysis relied on two different but complementary methods: a systematic review followed by a narrative review. This framework allowed us to give a comprehensive, quantitative and reproducible overview on the field while also enabling a more detailed analysis on several key points. However, our approach may suffer from some shortcomings. First, the definition and subsequent implementation of criteria to identify relevant papers in the systematic review entail some level of subjectivity. This may have led us to dismiss (or include) a small amount of papers not clearly falling in (or out) of the scope of this study. However, this kind of bias is hardly avoidable. Regarding the narrative review step, we focused on key points through a selection of examples, which entails a stronger bias. To mitigate this, we based our choices not only on our experience in the field of forest sector modelling, but also on the current political issues in forestry and results from the quantitative analysis. Even though some level of subjectivity persists, we believe such a choice was necessary in order to provide a more in-depth analysis of our topic.

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