Prospective analysis in the forest sector when facing environmental challenges : insights from large-scale bioeconomic modelling

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Prospective analysis in the forest sector when facing environmental challenges: insights from large-scale bio-economic modelling

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"Be yourself, everyone else is already taken"

- Oscar Wilde

List of publications

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Table of contents

List of figures

List of tables

Introduction

Context and presentation of the chapters

Introduction

1. Context: the forest sector, global changes and large-scale modelling for prospective analysis

1.1. The forest sector stands at a crossroads of economic, environmental and social stakes

The second half of the 20th century and the 21st century are characterised by an awakening regarding environmental challenges worldwide. Issues at stake include, among others, global warming, the erosion of biodiversity, land degradation and habitat losses, water pollution (IPBES 2018, 2019; IPCC 2018, 2019). While all are important and often intertwined, anthropogenic climate change has by far garnered the most attention in both policy and science (IPCC 2018; J. Li, Wang, and Ho 2011; Oberthür and Kelly 2008). Since the pre-industrial era, human activities have indeed caused a global warming of approximately 0.8-1.2°C, and forecasts predict that, if emissions were to continue uninterrupted, a warming of 1.5°C could be reached before the middle of the century, with cascading consequences on weather patterns, extreme conditions and disturbance events, as well as the availability of resources (IPCC 2018). Over the past decades, the international community has been striving to mitigate climate change by reducing emissions and increasing carbon removals while acknowledging the need to adapt human activities to upcoming changes (e.g. UNFCCC 2015). Forests and the forest sector constitute important levers for mitigation but are also very likely to be impacted by global changes.

Forests are defined by the Food and Agricultural Organisation of the United Nations (FAO) as "land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent" (FAO 2018). They are a major component of landscapes in most parts of the world and, despite undergoing contrasted evolutions in different regions, they represent around 30% of land area at the global level (FAO and UNEP 2020). In Metropolitan France, forests are the second most common land-use and cover 31% of the country's area, a figure that has been rising for several decades (IGN 2019). The *forest sector* can be understood as the combination of an upstream segment consisting of forest management activities and of a downstream segment consisting of timber processing, transportation and marketing activities (Buongiorno 2014; Hansen, Panwar, and Vlosky 2014; Solberg 1986). The basic resource for the forest sector is timber, which has various applications in construction, furniture making, energy production and chemical extraction, at both industrial and artisanal scales. Such products are traded worldwide, and the forest sector supports an important economic activity (Hansen, Panwar, and Vlosky 2014; Y. Li, Mei, and Linhares-Juvenal 2019). In France for example, 39 million cubic meters of wood were commercialised in 2018 from domestic harvests and the sector provided 24 billion euros of added-value and over 350 000 jobs (VEM, 2020; FCBA, 2020). Due to the forest sector being located at the intersection with other sectors (e.g. energy, construction), its contributions to the economy also include induced effects beyond direct employment and value-added (Y. Li, Mei, and Linhares-Juvenal 2019). Owing to forests being a strong landmark locally and to the strong links between the resource and the industry, forests and the forest sector also participate in creating a "sense of place" in territories (Gunderson and Watson 2007; Stedman 2003).

The forest sector's potential to address environmental issues resides in its ability to provide goods and services beyond timber. These are often grouped under the concept of (forest) *ecosystem services*, which can be defined as "direct and indirect contributions of ecosystems to human well-being" (TEEB 2010). Ecosystem services have been the subject of a flourishing literature in the past decades (Díaz et al. 2018; Seppelt et al. 2011), including for forests (Aznar-Sánchez *et al.*, 2018)[1]. They are usually separated into several categories, such as provisioning, regulation and cultural services, and distinctions are often made between ecosystem structures and functions (underlying the services), benefits (to human societies), and services themselves (de Groot et al. 2010; Haines-Young and Potschin 2018). Forest ecosystem services include, among others, the production of timber, of energy, of non-wood forest products, of food (provisioning); carbon sequestration, air purification and regulation of water quantity and quality (regulation); landscape aesthetics, recreational activities and spiritual uses (cultural). Forests also harbour a significant share of biodiversity and associated habitats, which is an important support for many ecosystem services (Brockerhoff et al. 2017).

Forests are to a large extent managed ecosystems, and forest management can be defined as "the integration of silvicultural practices and business concepts in such a way as to best achieve a landowner's objectives"(Bettinger et al. 2017). The provision of timber and other objectives are linked: management practices affect several at a time, and the literature gives evidence about both synergies and tradeoffs (Brockerhoff et al. 2017; Duncker et al. 2012; Gamfeldt et al. 2013; Van Der Plas et al. 2016). As a result, in many parts of the world, multiple-purpose forest management practices are pursued, which, owing to the integration between upstream and downstream activities, affect the whole forest sector. Among forests managed globally, only 31% have production designated as the primary objective[2], while others have designated objectives such as "multiple use" (22%), "protection of soil and water" (12%), "biodiversity conservation" (11%) or "social services" (6%) (FAO 2020). In Europe, even though 53% of forests have production designated as their main objective, forest management follows sustainability principles that take into account, among others, economic activities, forests' contribution to mitigating climate change and habitat protection to ensure a slowdown of biodiversity erosion (Forest Europe 2015; Ministry of Agriculture 2016)[3]. The forest sector consequently stands at a crossroads of economic, environmental and social stakes, and is both leveraged and impacted by policy.

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[1] Several definitions and classifications exist for the concept, with varying degrees of emphasis on ecosystem functions, services and benefits and takes on relationships between ecosystems and people (Arico et al. 2005; Díaz et al. 2018; Haines-Young and Potschin 2010; TEEB 2010). Aspects have been investigated in the literature include classification (Fisher, Turner, and Morling 2009), economic valuation (Costanza et al. 2014), payments (Gómez-Baggethun et al. 2010) and mapping (Maes et al. 2012).

[2] Data from the State of the World's forests and Forest Resource Assessment (FRA) reports are given as shares of forests within data self-reported by countries. These routinely cover 90-95% of all forests worldwide. In the FRA classification, production includes both the production of timber (all uses) and non-timber forest products. A primary objective may not be the sole objective, but is preeminent.

[3] The Forest Europe process officially defined sustainable forest management in 1993 as"the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfill, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems" (MCPFE 1993), a definition later introduced in French law (*Article L1 - Code forestier - Légifrance*).

This can be illustrated by taking the example of global warming. Mitigation is enabled by two mechanisms: reducing emissions of greenhouse gases and removing carbon from the atmosphere, and the forest sector can contribute to both (Canadell and Raupach 2008; Favero, Daigneault, and Sohngen 2020; Luyssaert et al. 2018). On the one hand, wood-based products can be used as a source of energy or as material for construction instead of more carbon-intensive products such as oil and concrete, generating avoided emissions (Eriksson et al. 2012; Geng et al. 2017; Sathre and O'Connor 2010). On the other hand, forest management practices can be adapted to remove atmospheric carbon and sequester it in forest biomass, soils and long-lived timber products through e.g. afforestation, avoided deforestation, extended rotations or climate-smart management practices (Bonan 2008; Kindermann et al. 2008; G.-J. Nabuurs et al. 2017; Sedjo and Sohngen 2012; Yousefpour et al. 2018).

Despite this ability to contribute to mitigation, the forest sector will very likely be affected by climate change in return (and already is). The literature predicts increases in net primary productivity due to fertilisation effects which may however not be permanent (Lindner et al. 2010, 2014; Reyer et al. 2014), increases in background mortality (Archambeau et al. 2020; Senf et al. 2018; Taccoen et al. 2019), an evolution of species distribution ranges (Dyderski et al. 2018; Hanewinkel et al. 2013) and an increase in catastrophic mortality due to disturbance events (Reyer et al. 2017; Seidl et al. 2017; Seidl, Schelhaas, and Lexer 2011). These evolutions all have potential implications not only for timber production and downstream economic activities (Favero, Mendelsohn, and Sohngen 2018; Hanewinkel et al. 2013; Lindner et al. 2002), but also for the sector's mitigation abilities (Le Page *et al.*, 2013; Seidl *et al.*, 2014; Lobianco *et al.*, 2016) and the provision of other ecosystem services (Montoya and Raffaelli 2010; Mooney et al. 2009). Owing to the inertia inherent to forest systems, there is a need to adapt practices in the forest sector to anticipate such evolutions concurrently to mitigation efforts (Keenan 2015).

As a result of this double status, policy documents at the international, EU or national levels that formalise commitments and objectives often feature the forest sector[4]. On the one hand, forest policy explicitly states objectives to use forestry to mitigate climate change while also reminding economic and industrial goals, other forest uses as well as acknowledging the necessity to adapt practices to anticipated impacts (e.g. European Commission, 2013; Forest Europe, 2015; Ministry of Agriculture, 2016). On the other hand, because of its importance for many activities, the forest sector is also leveraged and affected by policy pertaining to other sectors. Energy and climate policy leverage forestry to produce renewable biomass and increase the *in situ* carbon sink (European Parliament and European Council 2018; MTES 2018), conservation policy establishes reserves in forested areas to protect habitats and biodiversity (European Commission 2015, 2020), trade policy sets up barriers to the trade of illegally-logged timber to halt deforestation (European Parliament and European Council 2010), and development policy leverages forestry to mitigate climate change (Angelsen et al. 2012).

[4] For the specific case of France, policy pertaining to different fields is decided at various levels. For example, forest policy is a national prerogative, but general orientations related to forestry are also agreed upon at the European level (e.g. EU forest strategy, Forest Europe process). On the other hand, energy, climate and trade policy are largely decided at the European level (European Commission 2003; Oberthür and Kelly 2008; Solorio et al. 2017), translated into national strategies MTES 2018) and can indirectly affect the forest sector (Kallio et al. 2018; Moiseyev et al. 2010; G.-J. Nabuurs, Arets, and Schelhaas 2018). Commitments are also negotiated at the international level, for example the Paris Agreement states the importance of mobilizing the carbon sink in forests (UNFCCC 2015).

1.2. Bio-economic forest modelling as a support for decision making

Policy often turns to science to support decision-making. Forests are complex ecosystems that develop over long periods, and results from actions taken today may not be witnessed for several decades. In addition, there is a large amount of uncertainty regarding environmental changes and ecosystem responses (Lindner et al. 2014) but also developments in human societies (Riahi et al. 2017). Such reasons often exclude performing natural experiments on the forest sector and, instead, modelling is commonly used as an investigation method. In this thesis, we understand models as representations of a target system in the real world, used to provide insight into both the "model world" and the real-world *target* (Frigg and Nguyen 2017; Gräbner 2018; Morgan 2012), and we focus on those with the forest sector as their target.

As mentioned previously, the forest sector ranges from forest management and operations to processing industries and timber markets. As a result, dynamics in the forest sector are of different natures, i.e. biological, ecological, technological, economic. Comprehensive modelling therefore requires tapping into several disciplines, commonly environmental and economic sciences[5] (Beaussier et al. 2019; Hamilton et al. 2015; Lindner et al. 2002): we group such approaches under the term of *bio-economic* modelling.

Furthermore, the forest sector can be apprehended at several spatial scales. We designate by *local scale* those ranging from the forest stand to the landscape. There, bio-economic forestry models largely derive from the seminal work of Faustmann (1849) on optimal rotation modelling and the Land Expectation Value (LEV) criterion. Faustmann's model tries to answer a seemingly simple question - "when should harvesting take place?" - by integrating economic reasoning together with information on forest growth. Indeed, original approaches use forest growth functions[6] together with the LEV criterion, while later developments use detailed, process-based or empirical forest growth simulators to account for biological dynamics (e.g. Brèteau-Amores, Brunette and Davi, 2019). Owing to its long history in forest economics, Faustmann's model has then been refined to introduce aspects such as non-timber amenities (Hartman 1976; van Kooten, Binkley, and Delcourt 1995) and risk associated to natural disturbances (Reed 1984). At the higher property or landscape scales, spatial planning models integrate the LEV-maximisation rationale with forest operation optimization (Shan et al. 2009), sometimes also considering non-timber amenities (Backéus, Wikström, and Lämås 2005; Raymer et al. 2009).

We designate by *large scale* the spatial scales ranging from the region to the global scales. Modelling then shifts away from individual forest owners and forest growth and focuses on timber resources, industries and material flows. Bio-economic models then tap into econometric models of timber supply and equilibrium market modelling on the one hand, and large-scale forest inventory or vegetation models on the other hand (e.g. Nabuurs, Schelhaas and Pussinen, 2000; Adams and Haynes, 2007; Toppinen and Kuuluvainen, 2010; Latta, Sjolie and Solberg, 2013). Such models are usually referred to as *Forest Sector Models* (FSMs) and, contrary to large-scale ecological models, e.g. inventory models or vegetation models where the focus on downstream activities is limited or absent, FSMs integrate feedbacks between forest resources, forest management and timber industries, often at the cost of a simplified

[5] Modelling approaches bridging economics and environmental sciences are common in issues pertaining to natural resources and ecosystems, and are not limited to forests. A more generic term for models integrating several fields of research is that of "integrated model".
[6] Harvestable timber volumes are usually defined as a function of stand age.

representation of ecological processes. FSMs are commonly used to perform prospective analysis, either as a form of "outlook study" – where one uses models and narratives to assess possible future developments – or as a form of "policy study" – where the implications of potential policy decisions are assessed (Adams and Haynes 2007; Daigneault et al. 2019; Hurmekoski and Hetemäki 2013; Sjølie, Latta, and Solberg 2016; Toppinen and Kuuluvainen 2010). Results are then often synthetized in reports destined to government agencies and other decision makers, usually provided by research and expert institutions such as the US Forest Service, the French Agricultural Research Institute (INRAE) or the European Forest Institute (e.g. FAO, 2010; Ince *et al.*, 2011; Roux *et al.*, 2017). This thesis focuses on large-scale FSMs and their uses, but also calls upon small-scale modelling.

Forecasting and prospective analysis

Several terms are encountered in the FSM literature to refer to the activity performed, e.g. "prospective", "forecasting", "scenario analysis", "projection". A broad distinction can be made between *prospective analysis* on the one hand, and *(classical) forecasting* on the other. *Forecasting* refers to a quantitative assessment, often associated to a degree of confidence or a probability, of the future values of a variable. In the classical sense, it is closely linked to the concept of *projection*, where one uses knowledge of past values and relationships to determine a (unique) future state. *Prospective* analysis – *la prospective* in French, *(strategic) foresight* in English – is a holistic approach based on the assumption that the future is multiple, uncertain and, being the realm of action, cannot be known in advance but remains to be built. *Prospective* analysis explores several possible futures ("*futuribles*") and paths leading to them through systemic, often trans-disciplinary approaches, with the objective to prepare for it (Godet 1982; Jouvenel 2004; Cuhls 2003; Godet et al. 2013; Wilkinson & Aldinow 2008).

For complex systems, Jouvenel (2004) identifies two general approaches to simulating the future: *models* and *scenarios*. The former relies on translating part of a target system into a set of equations used to perform *projections.* It is traditionally associated to *(classical) forecasting* in economics, and econometric times series models are a textbook example. On the other hand, the latter is generally associated to *prospective* and *foresight* studies and rely on crafting quantitative and qualitative narratives describing the path to a particular end point, and can be either *exploratory* or *normative*.

FSMs are numerical simulation models, partly based on econometrics and on the extrapolation of past observations, used to quantify future developments in a system represented by a fixed set of largely deterministic equations and rules. However, FSM research targets a large and complex system –the forest sector – and often integrates inputs from various disciplines. Research is usually performed in such a way that several possible futures are explored, and mixed quantitative-qualitative narratives are used to drive simulations, even though models eventually only accept quantified variables. Finally, FSMs are used in a pro-active manner, i.e. with the objective of preparing decision-making for the future, through both exploratory and normative approaches.

For these reasons, FSM research finds itself in an intermediary position between *classical forecasting* and *prospective analysis.* In this thesis, I adopt a pragmatic approach and consider that FSM research performs *prospective analysis* when it explores several possible futures without trying to precisely estimate a particular value, instead focusing on the identification of patterns and trends, with the objective of informing upcoming decision-making while acknowledging the limited scope of model-based simulations. The terms *forecast* and *projections* are used interchangeably throughout this thesis with the general meaning of *simulation results*, with no underlying claim regarding their likeliness or status as *predictions*.

FSMs were developed in the late 1970s to forecast developments in timber markets and resource use (Adams and Haynes 2007; Kallio, Dykstra, and Binkley 1987). Since then, FSM research has developed into its own research area within forest economics and modelling, new models have been developed and contributions to the topic have been numerous (Caurla 2013; Latta, Sjolie, and Solberg 2013). However, as forest policy increasingly integrates environmental stakes, part of the focus has shifted away from FSMs' original focus on timber markets and resources. Indeed, a significant proportion of recent research has been dealing with issues such as climate change (Favero, Daigneault, and Sohngen 2020; Guo and Gong 2017; Sjølie, Latta, and Solberg 2014; Tian et al. 2016), energy production (Caurla et al. 2018; Galik et al. 2015; Mustapha, Trømborg, and Bolkesjø 2017) or biodiversity and landscape conservation (Costanza et al. 2017; Kallio et al. 2008; Montgomery, Latta, and Adams 2006; Schleupner and Schneider 2013).

As models are used to answer questions further away from their original purpose, methodological boundaries are likely to emerge. Investigating environmental issues requires an extension of the models' target system. Downstream, new products, markets, industries and concepts need to be considered, e.g. bioenergy powerplants, the electricity sector, avoided emissions. Upstream, a finer level of detail in the representation of biological dynamics may be required, and new spatial scales may need to be addressed in order to e.g. assess non-timber amenities or model novel management practices. Every time new facts are considered, questions also arise regarding the choice and availability of data and theory used to represent them. Original methods may be improved to address novel issues (e.g. Latta, Baker and Ohrel, 2018; Wear and Coulston, 2019), methods from other fields can be adapted (e.g. Earles *et al.*, 2012; Sjølie, Latta and Solberg, 2016) but, sometimes, limits are harder to overcome. For example, the evolution of environmental and climatic conditions are uncertain, especially when it comes to extreme events (Lindner et al. 2014; Seidl et al. 2017) but, as pointed out by Chudy, Sjølie and Solberg (2016), risk and uncertainties have received a limited amount of attention in FSM research. In the light of such limitations, one can wonder if FSM research addresses the "right questions (i.e. those considered important by decision makers in national governments, forest industry or in the European Commission), or only the ones for which methods and sufficient data are available?" (Toppinen and Kuuluvainen 2010, about FSM research in Europe) and how obstacles can be overcome.

In this thesis, I propose an exploration of the ways FSM research addresses environmental stakes central to forest policy today, and seek to put forward methodological solutions for the treatment of policy-relevant questions through applied study cases for the French forest sector, with a particular emphasis on the upstream forest sector and climate change.

2. Research questions and presentation of the chapters

This thesis aims at answering the following general research question: **to what extent can forest sector models (FSMs) accompany forest policy-making in facing environmental challenges in the 21st century?** Research presented in this manuscript seeks to provide insight into this question by investigating several, more focused research questions (RQ 1-4), and the thesis can be understood as composed of two parts. The first part concerns models themselves, their relationship to decision making and how they may be used for prospective analysis addressing environmental stakes (RQ 1-2). The second part consists of applied study cases for France and addresses two facets of climate change, mitigation and adaptation, while also seeking to further model development (RQ 3-4). Each research question forms the core focus of a different chapter.

2.1. Chapter 1: Representations of the forest sector in economic models

In order to determine how FSMs can help face current environmental challenges, one must first understand their ties to forest policy and the mechanisms behind their ability to provide expertise and decision support, regardless of current trends. Therefore, the first chapter aims at answering the following question: **(RQ 1) What are forest sector models, and how does prospective analysis performed with them contribute to forest policymaking?**

The thought process begins with the introduction of models as *representations*, a concept taken from epistemological sciences (Morgan and Knuuttila 2012). Previous literature on forest sector modelling has shown that, despite their common origins, there exist a wide variety of FSMs (Latta, Sjolie, and Solberg 2013). FSMs being representations of the real-world forest sector, we hypothesize that this variety partly comes from the representation process, and we explore how the choice of facts being represented (i.e. the boundaries of the forest sector from the modeller's point of view) as well as that of the data, method or theory used for representation, are determinants of this variety.

FSM are applied models, generally used to answer policy-relevant questions, and they are routinely used in reports destined to policymakers (Adams and Haynes 2007; Toppinen and Kuuluvainen 2010). As a result, it would seem logical to assume that policy agendas also influence model-making and model use. In order to verify this intuition, we explore the FSM literature, both early and recent, and draw parallels with forest policy at the time and/or place where models are developed in order to highlight ties between the two. Nonetheless, we also nuance this claim by looking at how past model development partly conditions subsequent advances, and perform a network analysis to show that current FSM research remains structured along historical methodological and geographical axes. We finally invoke Mary Morgan's (2012) account of how economists conceive and use models to show that, while interactions between forest economists and FSMs are a classical example of human-model interaction, their inception, development and subsequent uses are all shaped by their end-use in policy analysis.

2.2. Chapter 2: Evolving integrated models from narrower economic tools: the example of forest sector models

In chapter 1, we recount how FSMs have been developed in the 1970s as a novel way of jointly forecasting developments in timber supply and forest resources, at a time when questions of resource depletion, multiple use forestry and sustainable management were emerging. Today, in the face of global environmental challenges, forest policy gives a lot of room to leveraging the forest sector's ability to mitigate climate change, produce renewable energy, preserve habitats, water, and meet societal demands. In parallel to policy shifting away from timber-centric questions towards wider sustainability issues, FSM research grew as a research field, particularly in the 2010s (Latta, Sjolie, and Solberg 2013; Toppinen and Kuuluvainen 2010). Owing to the strong ties between FSM research and forest policy, one can logically wonder whether the former has also shifted its focus to accompany evolutions in the latter, or not.

As a result, this second chapter seeks to answer the following question: **(RQ 2) To what extent has research in forest sector modelling investigated objectives other than the production of timber, and how?** We know from previous literature that FSM have indeed been used to address issues of "environment", "climate change" and "renewable energy" (Latta, Sjolie, and Solberg 2013). Therefore, our hypothesis is that FSM research does accompany forest policy in its transition. However, models are usually developed with specific questions in mind, hence we expect the integration of non-timber objectives to be both unequal and incomplete. Issues pertaining to cultural ecosystem services and some regulation services are usually less addressed by the general literature (Chan et al. 2012; Díaz et al. 2018), and data availability and quality are often concerns in FSM research (Kallio and Solberg 2018; Toppinen and Kuuluvainen 2010; Wear and Coulston 2019). Therefore, we expect some issues will be addressed more often than others, and we expect technical obstacles to the treatment of non-timber objectives in FSM.

To validate or infirm this hypothesis, a quantitative and narrative review of the literature is carried out, with several objectives. Namely, (1) to identify which non-timber objectives have been studied in FSM research, (2) to quantify the extent to which they have been investigated, (3) to give an overview of the methods used to address them, (4) to outline the perspective adopted in their investigation (i.e. what questions are being asked?), and finally (5) to elicit potential obstacles faced by FSM research in investigating non-timber objectives. From a more general perspective, the aim is also to document how an originally narrow tool has evolved, integrating new dimensions to address novel questions, and to highlight the challenges brought by this integration, drawing parallels to other modelling fields.

2.3. Study cases for the French forest sector

The second half of this thesis consists of applied study cases for the French Forest Sector (chapters 3 and 4). This study case is relevant for several reasons. First, because of the country's high level of diversity in environmental conditions. These encompass oceanic, continental and Mediterranean climates, lowland and mountainous areas and a wide range of soil types, resulting in very diverse forests with many marketable tree species and a resource primarily composed of broadleaf species (IGN 2019). Second, because of the way the sector is structured. 75% of forests are privately owned, but a majority of these belong to small-scale owners and large forest holdings are rare in most regions. The industry comprises a large number of small to medium-sized enterprises but a limited amount of large companies, which sets it apart from other heavily forested European countries (FCBA 2020). Third, because of important policy stakes. France is committed to an ambitious "zero net emissions" target for 2050 and strategies rely on the forest sector to reach it (MTES 2018). At the same time, the forest sector is considered to be in crisis and policies seek to improve its competitiveness, increase harvests and enhance innovation in industries (D'Amécourt et al. 2016; Ministry of Agriculture 2016). Meanwhile, the need to adapt practices to environmental changes is also at the forefront of the agenda, as droughts, wildfires and pest outbreaks multiply (Chatry 2010).

The study cases also anchor this thesis within the wider research project in forest sector modelling performed at the Bureau d'Economie Théorique et Appliquée (BETA). While FSM research appeared in some countries in the 1970s, it is a rather recent research endeavour in France and began in 2008 when, within the framework of a PhD project in collaboration with the French Forest Agency ONF (Caurla 2012), the French Forest Sector Model (FFSM) was developed[7]. The first version, called FFSM 1.0 (Caurla et al. 2010), is a recursive dynamic model with ties to models of the "IIASA-GTM[8]" family of models developed elsewhere in Europe (e.g. Kallio, Moiseyev and Solberg, 2004; Trømborg and Sjølie, 2011) as well as with the Global Forest Products Model (GFPM, Buongiorno *et al.*, 2003). Similarly to these other models, the FFSM couples an aggregated matrix-based representation of forest inventories to a spatial equilibrium market model based on Samuelson's (1952) mathematical programming solution to forecast developments in the forest sector. FFSM 1.0 was focused on the short-to-medium term and downstream timber uses. It has been used to investigate the potential of using forest-based bioenergy to mitigate climate change (Caurla et al. 2013a, 2013b, 2018; Lecocq et al. 2011), the economic implications of a post-storm recovery plan (Caurla, Garcia, and Niedzwiedz 2015) and to perform a material flow analysis within timber industries (Lenglet, Courtonne, and Caurla 2017).

More recently, the FFSM research team operated a shift towards the upstream forest sector (resources and forestry), setting it apart from other models where a strong focus was put on downstream energy uses (e.g. Johnston and van Kooten 2016; Kallio et al. 2011; Mustapha, Trømborg, and Bolkesjø 2017; Peter and Niquidet 2016). A new version, called FFSM++, was developed in three steps[9]. First, the forest resource model was downscaled to the level of 8km pixels, enabling the representation of heterogeneous environmental conditions (Lobianco et al. 2015). Second, forest management decisions were made endogenous by embedding Faustmann's model at the pixel level (Lobianco et al. 2016). Third, similarly to other models (Wear and Coulston 2019), a carbon accounting module was developed to quantify mitigation possibilities (Lobianco et al. 2016). These developments paved the way for investigating issues related to (1) the state of forest resources and (2) management practices. An example is found in Petucco, Lobianco and Caurla (2019), who investigated the consequences of a pathogen invasion, but these new capacities largely remain to be leveraged.

In addition to model development strictly speaking, the FFSM team has also started to investigate wider environmental issues by the means of model couplings, i.e. studies where the FFSM is used conjunctly with other modelling frameworks, usually from a different discipline. These includes material flow analysis (Lenglet, Courtonne, and Caurla 2017), life-cycle analysis (Beaussier 2020), energy modelling (Caurla et al. 2018) and land-use modelling (Delacote *et al.*, in print).

My research takes place within the laboratory's wider research project, replaces itself within the trends outlined above, and builds upon research in the team. From a methodological point of view, study cases seek to leverage and further recent developments in the FFSM, and therefore focus on the upstream forest sector, the spatial representation of dynamics, and establish model couplings. From a thematic point of view, they complement previous work on climate change mitigation by focusing on carbon sequestration in forests, associated management changes, and risks of non-permanence through the lens of wildfire danger. These two latter points also bridge the gap with research performed at BETA outside the FFSM unit (Brèteau-Amores et al. 2020; Brèteau-Amores, Brunette, and Davi 2019).

[7] A first model of the forest sector in Eastern France (FIBRE) based on Systems Dynamics was developed by Lönnstedt and Peyron (1989) but was not used subsequently and has no ties to the FFSM.
[8] As explained in the first chapter, the International Institute for Advances Systems Analysis (IIASA) was a major cluster for early model development. The IIASA-Global Trade Model (IIASA-GTM) was later declined in several European countries.
[9] Details about the FFSM model can be found in Appendix A.

2.4. Chapter 3: Landscape implications of managing forests for carbon sequestration

The ability of forests to store carbon in biomass and products has received considerable attention in both science (e.g. Canadell and Raupach, 2008; Luyssaert *et al.*, 2018) and policy (e.g. Paris Agreement, Art. 5), and schemes for offset payments are available in a variety of countries today, including France (Ecosystem Marketplace 2017; JORF 2018). Sequestration and management changes required to make it happen have been extensively treated in forest economics at the local scale. Examples are numerous at both the stand scale (e.g. van Kooten, Binkley and Delcourt, 1995; Gutrich and Howarth, 2007a; West *et al.*, 2019) and the property or small landscape scale (e.g. Hennigar, MacLean and Amos-Binks, 2008; Raymer *et al.*, 2009; Liu, Lin and Su, 2017). This literature provides evidence that, in order to realize the mitigation potential of the forest sector, changes in management practices are needed, such as extending rotation times, changing operation timing or using new species, with implications for forest landscapes and the provision of other ecosystem services.

On the opposite, at the sectoral scale, the high level of spatial aggregation and the simplified representation of forest resources in models hinder the investigation of such questions. As a result, the literature is both scarcer and more focused on market implications (e.g. Buongiorno and Zhu, 2013; Guo and Gong, 2017; Pohjola *et al.*, 2018). More generally, as we show in chapter 2, the larger part of the literature at the sectoral scale focuses on mitigation through downstream uses in energy (e.g. Buongiorno, Raunikar and Zhu, 2011; Caurla, Delacote, Lecocq and Barkaoui, 2013; Moiseyev, Solberg and Kallio, 2013) and on the overall balance between energy and carbon sequestration (e.g. Kallio, Salminen and Sievänen, 2013; Eriksson, 2015; Favero, Daigneault and Sohngen, 2020).

Implications of carbon sequestration strategies for the upstream forest sector may be addressed by using a regional model with an endogenous representation of management practices and a finer level of detail in the representation of forest resources[10]. Besides, the local context is known to be an important determinant of sequestration possibilities, which vary across space (Adams et al. 2011; van Kooten et al. 2004; Yousefpour et al. 2018)

Following from these observations, this chapter seeks to answer the following question **(RQ 3) At the sectoral scale, what are the implications for forestry and forest landscapes of management practices aiming at both storing carbon and producing timber?** To investigate this issue, we embed Hartman's (1976) model of optimal rotations with non-timber amenities into the FFSM, using recent estimates of the social value of mitigation activities in France (Quinet 2019). This allows owners at the pixel level to consider forestry's contribution to climate mitigation through sequestration when making decisions and leverages the model's ability to represent a myriad of individual decisions across heterogeneous environmental conditions. While we expect market-level dynamics to follow trends highlighted in other sectoral studies (i.e. decreases in harvests, price increases), we assume that these latter refinements will highlight contrasted situations in forest management and landscapes across space over the long term, as owners in different locations change their practices.

[10] As we explain in the literature review of chapter 3, several such studies have been conducted for the western USA, with a strong focus on possibilities to afforest agricultural land to store carbon (Adams et al., 2011; Haim, White and Alig, 2015; Galik et al., 2016).

2.5. Chapter 4: Forests under threat: assessing wildfire risk and climate-driven uncertainty in a large-scale forest model

Chapter 3 highlighted that management practices can be altered to improve the forest sector's ability to mitigate climate change by storing carbon. However, contrary to avoided emissions, stored carbon is subject to risks of non-permanence, i.e. carbon can be released back into the atmosphere (Gren and Zeleke Aklilu 2016). Such risks are associated to disturbances, i.e. ''relatively discrete events that disrupt the structure of an ecosystem, community, or population, and change resource availability or the physical environment'' (Pickett and White 1985) which, for forests, encompass droughts, storms, pest and disease outbreaks and wildfires (Schelhaas, Nabuurs, and Schuck 2003). The term "disturbance regime" refers to the "spatial and temporal dynamics of disturbances over a longer time period" (Turner 2010) and relates to notions of spatial distribution (where does it happen?) frequency (how often?), size (what is the area affected?), intensity (how much energy is liberated?) and severity (what are the impacts?). Climate change is a key driver behind the evolution of disturbance regimes, which are expected to become more severe and reach new areas (Lindner *et al.*, 2010, 2014; Seidl, Schelhaas and Lexer, 2011; Seidl *et al.*, 2017), prompting management practices to adapt while raising concerns regarding implications for climate regulation (Le Page et al. 2013; Reyer et al. 2017; Seidl et al. 2014).

While the question of disturbance risk and adaptation has been an important topic for bio-economic forest modelling at the local scale (e.g. Couture and Reynaud, 2011; Daigneault, Miranda and Sohngen, 2015; Brèteau-Amores, Brunette and Davi, 2019), we show in chapter 2 that, at the sectoral scale, the question has remained a minor focus. From a more general perspective, risks and uncertainties have been but marginally treated in the FSM literature (Chudy, Sjølie, and Solberg 2016).

Wildfires are a common disturbance at the global level (Curtis et al. 2018) and, while they are part of natural processes (Pausas and Keeley 2019), they may have adverse economic, environmental and social consequences (Gill, Stephens, and Cary 2013). Fire occurrence, behavior and effects are highly stochastic and largely depend on local physical, environmental and weather conditions (Flannigan et al. 2009; Ruffault and Mouillot 2017). As a result, their integration into large-scale modelling frameworks constitutes an ongoing challenge (Hantson et al. 2016). In France, wildfires mostly affect the South-Eastern corner of the country, but they are expected to reach new areas in the decades to come while also becoming more severe and more frequent (Chatry 2010; Dupuy et al. 2020; Fargeon et al. 2020). By taking the example of wildfires, we seek to answer the following question:

- **(RQ 4a) How do climate-induced uncertainties propagate in FSM projections?**
- **(RQ 4b) What are the consequences for the forest sector of climate-induced changes in wildfire regimes?**

We tackle these questions by first reviewing the literature on fire risk and fire modelling, and we propose and develop a coupling between the FFSM and a probabilistic model of fire activity (Pimont et al. in print). Once the coupling is established, we perform stochastic simulations under several levels of radiative forcing and with data from different Global Circulation Models as inputs. We subsequently adapt uncertainty-partitioning methods from the climate science literature (Hawkins and Sutton 2009; Lehner et al. 2020) to quantify how climate-induced uncertainties propagate from the climate system to the forest sector.

While chapters 1-3 follow the structure of scientific articles, chapter 4 follows such a structure more loosely and we chose to highlight the research process in addition to results in the strict sense. The choices made, including options that were considered but eventually abandoned, are explained with more detail, and the discussion comprises exploratory analyses for further research.

References

Adams, Darius M, Ralph Alig, Greg Latta, and Eric M White. 2011. "Regional Impacts of a Program for Private Forest Carbon Offset Sales." *Journal of Forestry* 109(8): 444–61.

Adams, Darius Mainard, and Richard W. Haynes. 2007. *Resource and Market Projections for Forest Policy Development : Twenty-Five Years of Experience with the U.S. RPA Timber Assessment*. Springer.

Angelsen, A, M Brockhaus, WD Sunderlin, and L Verchot. 2012. Analysing REDD+: Challenges and choices *Analysing REDD+: Challenges and Choices*. Center for International Forestry Research (CIFOR).

Archambeau, Juliette et al. 2020. "Similar Patterns of Background Mortality across Europe Are Mostly Driven by Drought in European Beech and a Combination of Drought and Competition in Scots Pine." *Agricultural and Forest Meteorology* 280.

Arico, Salvatore et al. 2005. *Millenium Ecosystem AssessemnEcosystems and Human Well Being*.

Aznar-Sánchez, José A Belmonte-Ureña, Luis J., María J. López-Serrano, and Juan F. Velasco-Muñoz. 2018. "Forest Ecosystem Services: An Analysis of Worldwide Research." *forests* 9: 1–19.

Backéus, Sofia, Peder Wikström, and Tomas Lämås. 2005. "A Model for Regional Analysis of Carbon Sequestration and Timber Production." *Forest Ecology and Management* 216(1–3): 28–40.

Beaussier, Thomas. 2020. "Évaluation Économique et Environnementale Du Développement Régional d'une Filière En Interaction Multi-Secteur et Multi-Échelle : Cas de La Filière Forêt-Bois Du Grand Est." UNIVERSITÉ DE LORRAINE.

Beaussier, Thomas, Sylvain Caurla, Véronique Bellon-Maurel, and Eleonore Loiseau. 2019. "Coupling Economic Models and Environmental Assessment Methods to Support Regional Policies: A Critical Review." *Journal of Cleaner Production* 216: 408–21.

Bettinger, Pete, Kevin Boston, Jacek P. Siry, and Donald L. Grebner. 2017. "Management of Forests and Other Natural Resources." *Forest Management and Planning*: 1–20.

Bonan, Gordon B. 2008. "Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests." *Science* 320(5882): 1444–49.

Brèteau-Amores, Sandrine, Marielle Brunette, and Hendrik Davi. 2019. "An Economic Comparison of Adaptation Strategies Towards a Drought-Induced Risk of Forest Decline." *Ecological Economics* 164: 106294.

Brockerhoff, Eckehard G. et al. 2017. "Forest Biodiversity, Ecosystem Functioning and the Provision of Ecosystem Services." *Biodiversity and Conservation* 26(13): 3005–35.

Buongiorno, Joseph et al. 2003. "GFPM Structure and Formulation." In *The Global Forest Products Model*, Academic, 39–55.

———. 2014. "Global Modelling to Predict Timber Production and Prices: The GFPM Approach." *Forestry* 88(3): 291–303.

Buongiorno, Joseph, Ronald Raunikar, and Shushuai Zhu. 2011. "Consequences of Increasing Bioenergy Demand on Wood and Forests: An Application of the Global Forest Products Model." *Journal of Forest Economics* 17(2): 214–29.

Buongiorno, Joseph, and Shushuai Zhu. 2013. "Consequences of Carbon Offset Payments for the Global Forest Sector." *Journal of Forest Economics* 19(4): 384–401.

Canadell, Josep G, and Michael R Raupach. 2008. "Managing Forests for Climate Change Mitigation." *Science* 320: 1456–57.

Caurla, S., 2012. Modélisation de la filière forêt-bois françaiseÉvaluation des impacts des politiques climatiques (Doctoral dissertation).

Caurla, Sylvain, Philippe Delacote, Franck Lecocq, Julien Barthès, et al. 2013. "Combining an Inter-Sectoral Carbon Tax with Sectoral Mitigation Policies: Impacts on the French Forest Sector." *Journal of Forest Economics* 19(4): 450–61.

Caurla, Sylvain. 2013. "Une Typologie et Une Histoire Des Modèles Économiques de Secteur Forestier." *Revue Forestière Française* (2): 163–81.

Caurla, Sylvain, Vincent Bertrand, Philippe Delacote, and Elodie Le Cadre. 2018. "Heat or Power: How to Increase the Use of Energy Wood at the Lowest Cost?" *Energy Economics* 75: 85–103.

Caurla, Sylvain, Philippe Delacote, Franck Lecocq, and Ahmed Barkaoui. 2013. "Stimulating Fuelwood Consumption through Public Policies: An Assessment of Economic and Resource Impacts Based on the French Forest Sector Model." *Energy Policy* 63: 338–47.

Caurla, Sylvain, Serge Garcia, and Alexandra Niedzwiedz. 2015. "Store or Export? An Economic Evaluation of Financial Compensation to Forest Sector after Windstorm. The Case of Hurricane Klaus." *Forest Policy and Economics* 61: 30–38.

Caurla, Sylvain, Franck Lecocq, Philippe Delacote, and Ahmed Barkaoui. 2010. *The French Forest Sector Model: Version 1.0.*

Chan, Kai M.A. et al. 2012. "Where Are Cultural and Social in Ecosystem Services? A Framework for Constructive Engagement." *BioScience* 62(8): 744–56.

Chatry, Christian. 2010. "Rapport de La Mission Interministérielle Changement Climatique et Extension Des Zones Sensibles Aux Feux de Forêts"

Chudy, Rafal P., Hanne K. Sjølie, and Birger Solberg. 2016. "Incorporating Risk in Forest Sector Modeling – State of the Art and Promising Paths for Future Research." *Scandinavian Journal of Forest Research* 31(7): 719–27.

Costanza, Jennifer K., Robert C. Abt, Alexa J. McKerrow, and Jaime A. Collazo. 2017. "Bioenergy Production and Forest Landscape Change in the Southeastern United States." *GCB Bioenergy* 9(5): 924–39.

Costanza, Robert et al. 2014. "Changes in the Global Value of Ecosystem Services." *Global Environmental Change* 26(1): 152–58.

Couture, Stéphane, and Arnaud Reynaud. 2011. "Forest Management under Fire Risk When Forest Carbon Sequestration Has Value." *Ecological Economics* 70(11): 2002–11.

Cuhls, K., 2003. From forecasting to foresight processes—new participative foresight activities in Germany. *Journal of forecasting*, 22(2-3), pp.93-111.

Curtis, Philip G. et al. 2018. "Classifying Drivers of Global Forest Loss." *Science* 361(6407): 1108–11.

Daigneault, A. J., M. J. Miranda, and B. Sohngen. 2015. "Optimal Forest Management with Carbon Sequestration Credits and Endogenous Fire Risk." *Land Economics* 86(1): 155–72.

Daigneault, Adam et al. 2019. "Developing Detailed Shared Socioeconomic Pathway (SSP) Narratives for the Global Forest Sector." *Journal of Forest Economics* 34(1–2): 7–45.

DAmécourt, Antoine, François Houllier, Pierre-René Lemas, and Jean-Claude Sève. 2016. *Plan Recherche et Innovation 2025 Pour La Filière Forêt-Bois*.
Delacote, Philippe et al. "The Loop Effect : How Climate Change Impacts the Mitigation Potential of the French Forest Sector." *Journal of Forest Economics*: 1–64.
Díaz, Sandra et al. 2018. "Assessing Nature's Contributions to People: Recognizing Culture, and Diverse Sources of Knowledge, Can Improve Assessments." *Science* 359(6373): 270–72.
Duncker, Philipp et al. 2012. "How Forest Management Affects Ecosystem Services, Including Timber Production and Economic Return: Synergies and Trade-Offs." *Ecology and Society* 17(4): art50.
Dupuy, Jean-luc et al. 2020. "Climate Change Impact on Future Wildfire Danger and Activity in Southern Europe: A Review." *Annals of Forest Science* 77(2): 35.
Dyderski, Marcin K., Sonia Paź, Lee E. Frelich, and Andrzej M. Jagodziński. 2018. "How Much Does Climate Change Threaten European Forest Tree Species Distributions?" *Global Change Biology* 24(3): 1150–63.
Earles, J Mason, Anthony Halog, Peter Ince, and Kenneth Skog. 2012. "Integrated Economic Equilibrium and Life Cycle Assessment Modeling for Policy-Based Consequential LCA."
Ecosystem Marketplace. 2017. 7 Fertile Ground State of Forest Carbon Finance 2017 *Fertile Ground*. Washington DC.
Eriksson, Ljusk Ola et al. 2012. "Climate Change Mitigation through Increased Wood Use in the European Construction Sector-towards an Integrated Modelling Framework." *European Journal of Forest Research* 131(1): 131–44.
Eriksson, Mathilda. 2015. "The Role of the Forest in an Integrated Assessment Model of the Climate and the Economy." *Climate Change Economics* 6(3).
European Commission. 2003. "Forest Law Enforcement, Governance and Trade (FLEGT). Proposal for an EU Action Plan." *Governance An International Journal Of Policy And Administration*: 32.
———. 2013. Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions *A New EU Forest Strategy: For Forests and the Forest-Based Sector*.
———. 2015. *Natura 2000 and Forests. Part I - II*.
———. 2020. *A New EU Forest Strategy for Forests and the Forest-Based Sector*.
European Parliament, and European Council. 2010. *REGULATION (EU) No 995/2010 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 20 October 2010 Laying down the Obligations of Operators Who Place Timber and Timber Products on the Market*. Brussels: European Parliament and European Council.
———. 2018. *REGULATION (EU) 2018/841 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2018 on the Inclusion of Greenhouse Gas Emissions and Removals from Land Use, Land Use Change and Forestry in the 2030 Climate and Energy Framework, and Amending Regulation*.
FAO. 2018. *Terms and Definitions FRA 2020*.
———. 2020. Global Forest Resources Assessment 2020 *Global Forest Resources Assessment 2020*.
FAO and UNEP. 2020. *The State of the World's Forests 2020. Forests, Biodiversity and People.*
FAO, UNECE. 2010. Outlook *The European Forest Sector Outlook Study II*.
Fargeon, H et al. 2020. "Projections of Fire Danger under Climate Change over France: Where Do the Greatest Uncertainties Lie?" *Climatic Change* 160(3): 479–93.
Faustmann, Martin. 1849. "Berechnung Des Wertes Welchen Wladboden Sowie Noch Nicht Haubare Holzbestände Für Die Wladwirtschaft Besitzen [Calculation of the Value Which Forest Land and Immature Stands Possess for Forestry]." *Allgemeine Forst- und Jadg-Zeitung* 15: 441–55.
Favero, Alice, Adam Daigneault, and Brent Sohngen. 2020. "Forests: Carbon Sequestration, Biomass Energy, or Both?" *Science Advances* 6(13): eaay6792.
Favero, Alice, Robert Mendelsohn, and Brent Sohngen. 2018. "Can the Global Forest Sector Survive 11 °C Warming?" *Agricultural and Resource Economics Review* 47(2): 388–413.
FCBA. 2020. *Memento 2020*.
Fisher, Brendan, R. Kerry Turner, and Paul Morling. 2009. "Defining and Classifying Ecosystem Services for Decision Making." *Ecological Economics* 68(3): 643–53.
Flannigan, Mike D. et al. 2009. "Implications of Changing Climate for Global Wildland Fire." *International Journal of Wildland Fire* 18(5): 483–507.
Forest Europe. 2015. *Madrid Ministerial Declaration 25 Years Together Promoting Sustainable Forest Management in Europe*.
Frigg, Roman, and James Nguyen. 2017. "Models and Representation." In *Springer Handbooks*, Springer, 49–102.
Galik, Christopher S., Robert C. Abt, Gregory Latta, and Tibor Vegh. 2015. "The Environmental and Economic Effects of Regional Bioenergy Policy in the Southeastern U.S." *Energy Policy* 85: 335–46.
Gamfeldt, Lars et al. 2013. "Higher Levels of Multiple Ecosystem Services Are Found in Forests with More Tree Species." *Nature Communications* 4(1): 1340.
Geng, Aixin, Hongqiang Yang, Jiaxin Chen, and Yinxing Hong. 2017. "Review of Carbon Storage Function of Harvested Wood Products and the Potential of Wood Substitution in Greenhouse Gas Mitigation." *Forest Policy and Economics* 85: 192–200.
Gill, A. Malcolm, Scott L. Stephens, and Geoffrey J. Cary. 2013. "The Worldwide 'Wildfire' Problem." *Ecological Applications* 23(2): 438–54.
Godet, M., 1982. From forecasting to 'la prospective'a new way of looking at futures. *Journal of Forecasting*, 1(3), pp.293-301.
Godet, Michel, Philippe Durance, and Adam Gerber. "Strategic Foresight La Prospective Use and Misuse of Scenario Building." *The Circle of Future Entrepreneurs* 65, no. 1 (2013): 421.
Gómez-Baggethun, Erik, Rudolf de Groot, Pedro L. Lomas, and Carlos Montes. 2010. "The History of Ecosystem Services in Economic Theory and Practice: From Early Notions to Markets and Payment Schemes." *Ecological Economics* 69(6): 1209–18.
Gräbner, Claudius. 2018. "How to Relate Models to Reality? An Epistemological Framework for the Validation and Verification of Computational Models." *JASSS* 21(3).

Gren, Ing-Marie, and Abenezer Zeleke Aklilu. 2016. "Policy Design for Forest Carbon Sequestration: A Review of the Literature."
de Groot, R. S. et al. 2010. "Challenges in Integrating the Concept of Ecosystem Services and Values in Landscape Planning, Management and Decision Making." *Ecological Complexity* 7(3): 260–72.
Gunderson, Kari, and Alan Watson. 2007. "Understanding Place Meanings on the Bitterroot National Forest, Montana." *Society and Natural Resources* 20(8): 705–21.
Guo, Jinggang, and Peichen Gong. 2017. "The Potential and Cost of Increasing Forest Carbon Sequestration in Sweden." *Journal of Forest Economics* 29: 78–86.
Gutrich, John, and Richard B. Howarth. 2007. "Carbon Sequestration and the Optimal Management of New Hampshire Timber Stands." *Ecological Economics* 62(3–4): 441–50.
Haines-Young, Roy H, and Marion B Potschin. 2010. Ecosystems ecology: a new synthesis *The Links between Biodiversity, Ecosystem Services and Human Well-Being*.
Haines-Young, Roy, and Marion B. Potschin. 2018. European Environment Agency *Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure*. www.cices.eu (June 12, 2019).
Hamilton, Serena H et al. 2015. "Integrated Assessment and Modelling: Overview and Synthesis Ofsalient Dimensions." *Environmental Modelling and Software* 64: 215–29.
Hanewinkel, Marc et al. 2013. "Climate Change May Cause Severe Loss in the Economic Value of European Forest Land." *Nature Climate Change* 3(3): 203–7.
Hansen, Eric, Rajat Panwar, and Richard Vlosky. 2014. *Global Forest Sector*.
Hantson, Stijn et al. 2016. "The Status and Challenge of Global Fire Modelling." *Biogeosciences* 13(11): 3359–75.
Hartman, Richard. 1976. "The Harvesting Decision When A Standing Forest Has Value." *Economic Inquiry* XIV(March): 52–58.
Hawkins, Ed, and Rowan Sutton. 2009. "The Potential to Narrow Uncertainty in Regional Climate Predictions." *Bulletin of the American Meteorological Society* 90(8): 1095–1107.
Hennigar, Chris R., David A. MacLean, and Luke J. Amos-Binks. 2008. "A Novel Approach to Optimize Management Strategies for Carbon Stored in Both Forests and Wood Products." *Forest Ecology and Management* 256(4): 786–97.
Hurmekoski, Elias, and Lauri Hetemäki. 2013. "Studying the Future of the Forest Sector: Review and Implications for Long-Term Outlook Studies." *Forest Policy and Economics* 34: 17–29.
IGN. 2019. *Le Mémento - Inventaire Forestier 2019*.
Ince, Peter J et al. 2011. "U.S. Forest Products Module: A Technical Document Supporting the Forest Service 2010 RPA Assessment."
IPBES. 2018. *The Assessment Report on Land Degradation and Restoration: Summary for Policymakers*.
———. 2019. *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*.
IPCC. 2018. Ipcc - Sr15 *Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response*.
———. 2019. *IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security and Greenhouse Gas Fluxes in Terrestrial Ecosystems*.
Johnston, Craig M.T., and G. Cornelis van Kooten. 2016. "Global Trade Impacts of Increasing Europe's Bioenergy Demand." *Journal of Forest Economics* 23: 27–44.
JORF. 2018. *Décret N° 2018-1043 Du 28 Novembre 2018 Créant Un Label « Bas-Carbone »*. Paris. https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000037657959&categorieLien=id (July 23, 2019).
Jouvenel, H de. and Fish, H., 2004. *Invitation à la prospective*. Futuribles.
Kallio, A. M I, O. Salminen, and R. Sievänen. 2013. "Sequester or Substitute-Consequences of Increased Production of Wood Based Energy on the Carbon Balance in Finland." *Journal of Forest Economics* 19(4): 402–15.
Kallio, A. Maarit I., and Birger Solberg. 2018. "On the Reliability of International Forest Sector Statistics: Problems and Needs for Improvements." *Forests* 8(2): 407.
Kallio, A. Maarit I, Perttu Anttila, Megan McCormick, and Antti Asikainen. 2011. "Are the Finnish Targets for the Energy Use of Forest Chips Realistic-Assessment with a Spatial Market Model." *Journal of Forest Economics* 17(2): 110–26.
Kallio, A. Maarit I, Riitta Hänninen, Nina Vainikainen, and Sandra Luque. 2008. "Biodiversity Value and the Optimal Location of Forest Conservation Sites in Southern Finland." *Ecological Economics* 67(2): 232–43.
Kallio, A Maarit I, Alexander Moiseyev, and Birger Solberg. 2004. "The Global Forest Sector Model EFI-GTM. The Model Structure." *EFI technical report* 15(15): 24.
Kallio, A Maarit I, Birger Solberg, Liisa Käär, and Risto Päivinen. 2018. "Economic Impacts of Setting Reference Levels for the Forest Carbon Sinks in the EU on the European Forest Sector." *Forest Policy and Economics* 92(May): 193–201.
Kallio, Markku, Dennis P. Dykstra, and Clark S. Binkley. 1987. *The Global Forest Sector: An Analytical Perspective*. Laxemburg.
Keenan, Rodney J. 2015. "Climate Change Impacts and Adaptation in Forest Management: A Review." *Annals of Forest Science* 72(2): 145–67.
Kindermann, Georg et al. 2008. "Global Cost Estimates of Reducing Carbon Emissions through Avoided Deforestation." *Proceedings of the National Academy of Sciences* 105(30): 10302–7. http://www.pnas.org/content/105/30/10302.full.pdf (November 13, 2017).
van Kooten, G. Cornelis, Clark S. Binkley, and Gregg Delcourt. 1995. "Effect of Carbon Taxes and Subsidies on Optimal Forest Rotation Age and Supply of Carbon Services." *American Journal of Agricultural Economics* 77(2): 365.
van Kooten, G. Cornelis, Alison J Eagle, James Manley, and Tara Smolak. 2004. "How Costly Are Carbon Offsets? A Meta-Analysis of Carbon Forest Sinks." *Environmental Science and Policy* 7(4): 239–51.
Latta, Gregory S., Justin S. Baker, and Sara Ohrel. 2018. "A Land Use and Resource Allocation (LURA) Modeling System for Projecting Localized Forest CO2effects of Alternative Macroeconomic Futures." *Forest Policy and Economics* 87(October 2017): 35–48.

Latta, Gregory S., Hanne K. Sjolie, and Birger Solberg. 2013. "A Review of Recent Developments and Applications of Partial Equilibrium Models of the Forest Sector." *Journal of Forest Economics* 19(4): 350–60.
Lecocq, Franck et al. 2011. "Paying for Forest Carbon or Stimulating Fuelwood Demand? Insights from the French Forest Sector Model." *Journal of Forest Economics* 17(2): 157–68.
Lehner, Flavio et al. 2020. "Partitioning Climate Projection Uncertainty with Multiple Large Ensembles and CMIP5/6." *Earth System Dynamics* 11(2): 491–508.
Lenglet, Jonathan, Jean-Yves Courtonne, and Sylvain Caurla. 2017. "Material Flow Analysis of the Forest-Wood Supply Chain: A Consequential Approach for Log Export Policies in France." *Journal of Cleaner Production* 165: 1296–1305.
Li, Jinfeng, Ming Huang Wang, and Yuh Shan Ho. 2011. "Trends in Research on Global Climate Change: A Science Citation Index Expanded-Based Analysis." *Global and Planetary Change* 77(1–2): 13–20.
Li, Yanshu, Bin Mei, and Thaís Linhares-Juvenal. 2019. "The Economic Contribution of the World's Forest Sector." *Forest Policy and Economics* 100: 236–53.
Lindner, Marcus et al. 2002. "Integrated Forestry Assessments for Climate Change Impacts." *Forest Ecology and Management* 162(1): 117–36.
———. 2010. "Climate Change Impacts, Adaptive Capacity, and Vulnerability of European Forest Ecosystems." *Forest Ecology and Management* 259(4): 698–709.
———. 2014. "Climate Change and European Forests: What Do We Know, What Are the Uncertainties, and What Are the Implications for Forest Management?" *Journal of Environmental Management* 146: 69–83.
Liu, Wan Yu, Chun Cheng Lin, and Ke Hong Su. 2017. "Modelling the Spatial Forest-Thinning Planning Problem Considering Carbon Sequestration and Emissions." *Forest Policy and Economics* 78: 51–66.
Lobianco, Antonello, Sylvain Caurla, Philippe Delacote, and Ahmed Barkaoui. 2016. "Carbon Mitigation Potential of the French Forest Sector under Threat of Combined Physical and Market Impacts Due to Climate Change." *Journal of Forest Economics* 23: 4–26.
Lobianco, Antonello, Philippe Delacote, Sylvain Caurla, and Ahmed Barkaoui. 2015. "The Importance of Introducing Spatial Heterogeneity in Bio-Economic Forest Models: Insights Gleaned from FFSM++." *Ecological Modelling* 309–310: 82–92.
———. 2016. "Accounting for Active Management and Risk Attitude in Forest Sector Models An Impact Study on French Forests." *Environ Model Assess* 21: 391–405.
Lönnstedt, Lars, and Jean-Luc Peyron. 1989. "FIBRE : A French PC-Based Regional Forest Sector Model Applied to Burgundy." *Annales des Sciences Forestières* 46(2): 101–18.
Luyssaert, Sebastiaan et al. 2018. "Trade-Offs in Using European Forests to Meet Climate Objectives." *Nature* 562(7726): 259–62.
Maes, Joachim et al. 2012. "Mapping Ecosystem Services for Policy Support and Decision Making in the European Union." *Ecosystem Services* 1(1): 31–39.
MCPFE. 1993. "RESOLUTION H1 General Guidelines for the Sustainable Management of Forests in Europe." *Conference Proceedings. Ministry of Agriculture and Forestry, Helsinki, Finland.* (June): 1–5.
Ministère de la Transition Ecologique et Solidaire. 2018. *National Low Carbon Strategy Project: The Ecological and Inclusive Transition towards Carbon Neutrality*. Paris.
Ministry of Agriculture, Agrifood and Forestry. 2016. *THE NATIONAL FOREST AND WOOD PROGRAMME (PNFB)*. Paris.
Moiseyev, Alexander, Birger Solberg, and A. Maarit I. Kallio. 2013. "Wood Biomass Use for Energy in Europe under Different Assumptions of Coal, Gas and CO2 Emission Prices and Market Conditions." *Journal of Forest Economics* 19(4): 432–49.
Moiseyev, Alexander, Birger Solberg, Bruce Michie, and A. Maarit I Kallio. 2010. "Modeling the Impacts of Policy Measures to Prevent Import of Illegal Wood and Wood Products." *Forest Policy and Economics* 12(1): 24–30.
Montgomery, Claire A, Greg S Latta, and Darius M Adams. 2006. "The Cost of Achieving Old-Growth Forest Structure." *Land Economics* 82(2): 240–56.
Montoya, José M., and Dave Raffaelli. 2010. "Climate Change, Biotic Interactions and Ecosystem Services." *Philosophical Transactions of the Royal Society B: Biological Sciences* 365(1549): 2013–18.
Mooney, Harold et al. 2009. "Biodiversity, Climate Change, and Ecosystem Services." *Current Opinion in Environmental Sustainability* 1(1): 46–54.
Morgan, Mary S., and Tarja Knuuttila. 2012. "Models and Modelling in Economics." In *Philosophy of Economics*, , 49–87.
Morgan, MS. 2012. "The World in the Model: How Economists Work and Think."
Mustapha, W.F., E. Trømborg, and T.F. Bolkesjø. 2017. "Forest-Based Biofuel Production in the Nordic Countries: Modelling of Optimal Allocation." *Forest Policy and Economics* (September 2016): 1–10.
Nabuurs, G. J., M. J. Schelhaas, and A. Pussinen. 2000. "Validation of the European Forest Information Scenario Model (EFISCEN) and a Projection of Finnish Forests." In *Silva Fennica*, , 167–79.
Nabuurs, Gert-Jan et al. 2017. "By 2050 the Mitigation Effects of EU Forests Could Nearly Double through Climate Smart Forestry." *Forests* 8(12): 484. http://www.mdpi.com/1999-4907/8/12/484 (February 11, 2020).
Nabuurs, Gert-Jan, Eric J. M. M. Arets, and Mart-Jan Schelhaas. 2018. "Understanding the Implications of the EU-LULUCF Regulation for the Wood Supply from EU Forests to the EU." *Carbon Balance and Management* 13(1): 18.
Oberthür, Sebastian, and Claire Roche Kelly. 2008. "EU Leadership in International Climate Policy: Achievements and Challenges?" *International Spectator* 43(3): 35–50.
Le Page, Y. et al. 2013. "Sensitivity of Climate Mitigation Strategies to Natural Disturbances." *Environmental Research Letters* 8(1).
Pausas, Juli G, and Jon E Keeley. 2019. "Wildfires as an Ecosystem Service." *Frontiers in Ecology and the Environment* 17(5): 289–95.
Peter, Brian, and Kurt Niquidet. 2016. "Estimates of Residual Fibre Supply and the Impacts of New Bioenergy Capacity from a Forest Sector Transportation Model of the Canadian Prairie Provinces." *Forest Policy and Economics* 69: 62–72.
Petucco, Claudio, Antonello Lobianco, and Sylvain Caurla. 2019. "Economic Evaluation of an Invasive Forest Pathogen at a Large Scale: The Case of Ash Dieback in France." *Environmental Modeling and Assessment*.

Pickett, S. T.A., and P. S. White. 1985. "The Ecology of Natural Disturbance and Patch Dynamics." *The ecology of natural disturbance and patch dynamics.*
Pimont F., Fargeon H., Opitz T., Ruffault J., Barbero R., Martin StPaul N., Rigolot E., Riviere M., Dupuy JL., in print. Prediction of regional wildfire activity in the probabilistic Bayesian framework of Firelihood. Ecological Applications.
Van Der Plas, Fons et al. 2016. "Jack-of-All-Trades Effects Drive Biodiversity-Ecosystem Multifunctionality Relationships in European Forests." *Nature Communications* 7: 1–11.
Pohjola, Johanna, Jani Laturi, Jussi Lintunen, and Jussi Uusivuori. 2018. "Immediate and Long-Run Impacts of a Forest Carbon Policy—A Market-Level Assessment with Heterogeneous Forest Owners." *Journal of Forest Economics* 32: 94–105.
Quinet, Alain. 2019. *The Value for Climate Action A Shadow Price of Carbon for Evaluation of Investments and Public Policies Report by the Commission Chaired By*. Paris.
Raymer, Ann Kristin et al. 2009. "A Forest Optimisation Model Including Carbon Flows: Application to a Forest in Norway." *Forest Ecology and Management* 258(5): 579–89.
Reed, William J. 1984. "The Effects of the Risk of Fire on the Optimal Rotation of a Forest." *Journal of Environmental Economics and Management* 11(2): 180–90.
Reyer, Christopher et al. 2014. "Projections of Regional Changes in Forest Net Primary Productivity for Different Tree Species in Europe Driven by Climate Change and Carbon Dioxide." *Annals of Forest Science* 71(2): 211–25.
Reyer, Christopher P.O. et al. 2017. "Are Forest Disturbances Amplifying or Canceling out Climate Change-Induced Productivity Changes in European Forests?" *Environmental Research Letters* 12(3).
Riahi, Keywan et al. 2017. "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview." *Global Environmental Change* 42: 153–68.
Roux, Alice, Jean-François Dhôte, Claire Bastick, and Antoine Colin. 2017. *Quel Rôle Pour Les Forêts et La Filière Forêt-Bois Françaises Dans l'atténuation Du Changement Climatique ?*
Ruffault, Julien, and Florent Mouillot. 2017. "Contribution of Human and Biophysical Factors to the Spatial Distribution of Forest Fire Ignitions and Large Wildfires in a French Mediterranean Region." *International Journal of Wildland Fire* 26(6): 498–508.
Samuelson, Paul A. 1952. "Spatial Price Equilibrium and Linear Programming." *American Economic Review* 42(3): 283–303.
Sathre, Roger, and Jennifer O'Connor. 2010. "Meta-Analysis of Greenhouse Gas Displacement Factors of Wood Product Substitution." *Environmental Science and Policy* 13(2): 104–14.
Schelhaas, Mart Jan, Gert Jan Nabuurs, and Andreas Schuck. 2003. "Natural Disturbances in the European Forests in the 19th and 20th Centuries." *Global Change Biology* 9(11): 1620–33.
Schleupner, Christine, and Uwe A Schneider. 2013. "Allocation of European Wetland Restoration Options for Systematic Conservation Planning." *Land Use Policy* 30: 604–14.
Sedjo, Roger A., and Brent Sohngen. 2012. "Carbon Sequestration in Forests and Soils." *Ssrn*.
Seidl, Rupert et al. 2017. "Forest Disturbances under Climate Change." *Nature Climate Change* 7(6): 395–402.
Seidl, Rupert, Mart Jan Schelhaas, and Manfred J. Lexer. 2011. "Unraveling the Drivers of Intensifying Forest Disturbance Regimes in Europe." *Global Change Biology* 17(9): 2842–52.
Seidl, Rupert, Mart Jan Schelhaas, Werner Rammer, and Pieter Johannes Verkerk. 2014. "Increasing Forest Disturbances in Europe and Their Impact on Carbon Storage." *Nature Climate Change* 4(9): 806–10.
Senf, Cornelius et al. 2018. "Canopy Mortality Has Doubled in Europe's Temperate Forests over the Last Three Decades." *Nature Communications* 9(1).
Seppelt, Ralf et al. 2011. "A Quantitative Review of Ecosystem Service Studies: Approaches, Shortcomings and the Road Ahead." *Journal of Applied Ecology* 48(3): 630–36.
Shan, Yong, Pete Bettinger, Chris J. Cieszewski, and Rongxia Tiffany Li. 2009. "Trends in Spatial Forest Planning." *Mathematical and Computational Forestry and Natural-Resource Sciences* 1(2): 86–112.
Sjølie, Hanne K., Greg S. Latta, and Birger Solberg. 2014. "Impacts of the Kyoto Protocol on Boreal Forest Climate Change Mitigation." *Annals of Forest Science* 71(2): 267–77.
———. 2016. "Combining Backcasting with Forest Sector Projection Models to Provide Paths into the Future Bio-Economy." *Scandinavian Journal of Forest Research* 31(7): 708–18.
Solberg, Birger. 1986. "Forest Sector Simulation Models as Methodological Tools in Forest Policy Analysis (Norway)." *Silva Fennica* 20(4): 419–27.
Solorio, Israel, Helge Jörgens, Israel Solorio, and Pierre Bocquillon. 2017. "EU Renewable Energy Policy: A Brief Overview of Its History and Evolution." In *A Guide to EU Renewable Energy Policy*, , 23–42.
Stedman, Richard C. 2003. "Sense of Place and Forest Science: Toward a Program of Quantitative Research." In *Forest Science*, Oxford Academic, 822–29.
Taccoen, Adrien et al. 2019. "Background Mortality Drivers of European Tree Species: Climate Change Matters." *Proceedings of the Royal Society B: Biological Sciences* 286(1900).
TEEB. 2010. *The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of TEEB*.
Tian, Xiaohui et al. 2016. "Global Climate Change Impacts on Forests and Markets." *Environmental Research Letters* 11(3)
Toppinen, Anne, and Jari Kuuluvainen. 2010. "Forest Sector Modelling in Europe-the State of the Art and Future Research Directions." *Forest Policy and Economics* 12(1): 2–8.
Trømborg, Erik, and Hanne K Sjølie. 2011. "Data Applied in the Forest Sector Models NorFor and NTMIII." *INA fagrapport. Department of Ecology and Natural Resource Management Norwegian University of Life Sciences* 17.
Turner, Monica G. 2010. "Disturbance and Landscape Dynamics in a Changing World." *Ecology* 91(10): 2833–49.
UNFCCC. 2015. *ParisAgreement*. Paris: UN.
"VEM Filière Forêt-Bois – Veille Economique Mutualisée Filière Forêt-Bois." https://vem-fb.fr/ (November 4, 2020).
Wear, David N, and John W Coulston. 2019. "Specifying Forest Sector Models for Forest Carbon Projections." *Journal of Forest Economics* 34(1–2): 73–97.

West, Thales A P, Chris Wilson, Maria Vrachioli, and Kelly A Grogan. 2019. "Carbon Payments for Extended Rotations in Forest Plantations : Con Fl Icting Insights from a Theoretical Model." *Ecological Economics* 163(February): 70–76.
Wilkinson, Angela, and Esther Eidinow. "Evolving Practices in Environmental Scenarios: A New Scenario Typology." *Environmental Research Letters* 3, no. 4 (2008).
Yousefpour, Rasoul et al. 2018. "Realizing Mitigation Efficiency of European Commercial Forests by Climate Smart Forestry." *Scientific Reports* 8(1): 1–11.

Chapter 1

Representations of the forest sector in economic models

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Abstract

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

1. Introduction

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

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

In this article, we seek to highlight the determinants of the representation of facts in FSM, that is to say, we want to elicit and discuss what determines *which* facts are represented and shapes *how* they are represented. Through these determinants, we also seek to document how modelling practices have changed over time, why understanding these changes is important, and to discuss how they may evolve in the future. In a first section, we show that the representation of facts in FSM is dependent on features of the target, the forest sector, in particular its boundaries, the nature of the facts it comprises, and the roles played by empirical data and theory. In a second section, we argue that models are shaped by the historical context of their development. We recount how different methodologies were developed since the

1970s, with different goals, and highlight how research up to the present day has been conditioned by these early developments. In the third section, we focus on how the applied uses of FSM for decision support influences modelling practices. We highlight that facts are incorporated into scenarios used to perform simulations, forming narratives used for a dual purpose: provide support for decision-making and get a better understanding of model behaviour. Building on previous sections, we finally discuss why understanding these determinants is important for modellers, and how practices may evolve in the future.

2. The representation of facts in forest sector models depends on the features of their target, the forest sector

2.1. The forest sector: a complex target with unclear boundaries

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

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

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

Trømborg, Bolkesjø, and Solberg 2013; Mustapha, Trømborg, and Bolkesjø 2017). On the other hand, the French forest sector is characterised by a high degree of heterogeneity in environmental conditions and an industry that is less integrated: model development there focuses on representing diversity in forests and forestry practices (Lobianco *et al.*, 2015; Lobianco, Delacote, *et al.*, 2016).

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

2.2. Representations, theory and empirical data

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

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

Then, what type of models are FSM? Economists often establish a broad distinction between mathematical models, based on economic theory, and econometric models, which also incorporate elements of statistical theory (Morgan and Knuuttila, 2012). Even though econometrics play a role in representing the forest sector, FSM are to our opinion more akin to the former. FSM can also be considered computational models in the sense that they are composed of sets of procedures and rules, in particular regarding natural and technological facts, but also because they are used for simulation, "grow their results from the initial conditions", and sometimes do not allow for analytical proof (Gräbner, 2018, 5). FSM incorporate elements of positivity, i.e. representing what is, in their bottom-up, technical representation of many processes. This, as we will see in subsequent sections, partly relates to their development as applied tools for forest policy planning. However, this is often limited to processes that are well defined or central to the question studied (Buongiorno, 1996). For other facts, such as spatial equilibria or consumption behaviours, technical representations are harder to construct, either because there is a lack of data or a lack of understanding of the process. In these cases, theory-based optimisation algorithms or stylized equations may be used: because of this, FSM also incorporate normative elements, i.e. representing what ought to be.

2.3. Spatial and temporal dimensions in representing the forest sector

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

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

3. The representation of facts is influenced by the historical context of model development

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

3.1. Spatial equilibrium models and outlook studies for the forest sector

An important institution in developing early FSM was the US Forest Service, in charge of managing National Forests since 1901[11]. Gifford Pinchot, first head of the Forest Service and figure of the conservation movement, was an advocate for scientifically grounded, multiple-use management, highlighting the importance of resource permanence and sustainable yield. Following strong increases in forest use after Wold War II, the equality of several forest objectives was enshrined in the Multiple-Use Sustained-Yield Act of 1960. The Forest and Rangeland Renewable Resources Planning Act (RPA) of 1974 subsequently required the Forest Service to develop an integrated approach to forest planning based on long-term assessments, including economic considerations (Alston, 1972; Bowes and Krutilla, 1985; Wadsworth and Fedkiw, 2000; Williams, 2005). Assessments performed up to World War II (Graves, 1934; Hough, 1878) had largely relied on expert judgement, while assessments in the 1950-1980 period (US Forest Service, 1973, 1965, 1958) used "gap" models where demand and supply were forecast separately by extrapolating past trends. As stated by Adams and Haynes, these "were estimates of future demand and supply volumes at something other than equilibrium price" and showed their limits when prices became volatile in the 1970s (Adams and Haynes, 2007, 7). The RPA assessment system emphasised the importance of capturing supply-demand-price relationships as well as the regional nature of the sector in periodical assessment reports: research was orientated towards developing spatial price equilibrium (SPE) models. At the same time, a second research cluster developed at the International Institute for Applied Systems Analysis (IIASA), an institution founded in 1972 where research focused on developing global models. In particular, IIASA was involved in developing early Integrated Assessment Models (IAM) of the energy-climate system (Matarasso, 2007). There, the Global Forest Sector project, conceived in the late 1970s and launched in 1980, aimed to "study long-term developments in the production, consumption, and world trade of forest products", and would develop the first global FSM (Kallio et al., 1987, ix).

FSM from that period find part of their origin in the works of Koopmans and Dantzig on transportation systems, activity analysis and linear programming (Dantzig 1950; Koopmans 1949; 1951; 1953) and, more generally, in works at the Cowles Commission aiming at the mathematisation of economic problems, which were influential in developing other technical-economic models like IAM (Matarasso, 2007). Following the 1949 Cowles conference on "Activity analysis of production and allocation" (Dantzig *et al.*, 1951), Samuelson (1952) proposed a solution to SPE through resolution of a mathematical programming problem where net social payoff is maximised under a set of constraints. The solution was later refined using methods based on quadratic programming, linear approximations and extended to include activity analysis (Takayama and Judge 1970; 1964a; 1964b; Duloy and Norton 1975). As stated earlier, FSM also include econometric equations to represent supply and demand behaviours. Through these, they are related to econometric studies of wood products markets, such as the work of McKillop (1967). Some FSM also find part of their origin in the system dynamics (SD) framework proposed by Forrester (1969) and (used in the Club of Rome report (Meadows et al. 1972)), where emphasis is on change and the system's evolution is described by sets of rules and differential equations. A synthesis was proposed in the PELPS software (Gilless and Buongiorno, 1985), a modelling environment for

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

equilibrium models where static market equilibria are described with econometric equations and activity analysis, solved with mathematical programming, following which a "dynamic phase" akin to SD recursively updates conditions (Buongiorno, 1996).

3.2. Timber supply models, optimal harvesting and the economics of natural resources

A second approach is found in supply models (SM) developed at Resources for the Future (RFF), a research institution which, since the 1950s, focused on resource and environmental economics, particularly dealing with scarcity issues (Pearce, 2002). SM first find their root in the optimal harvesting problem, which is concerned with answering one of the oldest questions in forest economics: "when is it optimal to cut a tree/stand?" Early contributions date back to the 18th century and include thoughts and experiments by De Fenille (179), Duhamel du Monceau (1764) and Hartig (Baudrillart, 1805). The solution as we know it today was proposed by Faustmann (1849) in his optimal rotation model where the present value of forest rents from an infinite repetition of forest rotations, or land expectation value, is maximised. Even though his model did not immediately disseminate (Peyron, 1999), it came back to the forefront following Samuelson's (1976) essay reconciling it with modern economics and subsequent extensions to non-timber amenities (Hartman, 1976) and risk (Reed, 1984). SM find their second root in Hotelling's (1931) well known model of the optimal use of non-renewable resources over time. These were adapted to the optimal harvesting of old-growth forests, considered non-renewable resources (Lyon and Sedjo, 1986). Other forest-related concerns at RFF at that time included steady-state forestry, multiple-use forestry and conservation economics (e.g. Bowes and Krutilla, 1989, 1985; Hyde, 1980).

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

3.3. FSM subsequent development was driven by model-based policy expertise

As stated by Solberg in an early contribution, FSM's main purpose is to perform forest policy analysis, i.e. the "analysis of the effects of forest policy means" (Solberg, 1986, 420). From the 1980s onwards, FSM have continued to be developed in close relationship with institutions in charge of or interested in forest policy and planning and, over the years, they have been used as tools for prospective analysis in the forest sector and used to perform outlook studies (Hurmekoski and Hetemäki, 2013). The development of FSM thus replaces itself within a more general trend of using mathematical simulation models for policy planning. As recounted by Maas, mathematical "structural models" based on econometrics and developed at the Cowles commission had been dismissed in the 1950s because of the low accuracy of their predictions

(Maas, 2014, 76-98). Model simulations came back to the forefront of economics in the 1970s, when the utility of structural models was recognised not to be in predicting, but rather in their capacity to forecast and explore possible courses of action. They were in particular developed by the Central Planning Bureau and later the Central Bank of the Netherlands as part of their planning process, and contributed to "the reinforcement of the bank's position in policy preparation" (Maas 2014, 150-156). As a result, FSM are related to many other types of 'structural' models developed since that time for various sectors, which seek to capture the "underlying structure" and "causal connections" within economies (Maas 2014, 81).

Work at the US Forest Service yielded models of North-American solid wood products and pulp and paper markets used for all RPA assessments up to 2005 (Adams and Haynes, 2007). With similar methods, the global GFPM model was developed and in the FAO's 1999 global forest products outlook study (Zhu, Buongiorno and Tomberlin, 1998; Tomberlin, Buongiorno and Zhu, 1999). In an effort to anchor national RPA assessments within an international context, a national-level derivative was created and used in post-2005 RPA assessments (Ince *et al.*, 2011). The Forest Service was also involved alongside several universities in developing FASOM, a model of the US forest and agricultural sectors, which draws on both strands of early FSM (Adams et al. 1996)[12]. It was used to assess climate and energy policy (Beach and McCarl, 2010), and adapted for Europe (Schneider et al. 2008) and the pacific north-west (Adams and Latta 2005).

In Europe, IIASA's Global Forest Sector project yielded the global SPE model GTM (Kallio, Dykstra and Binkley, 1987), but also a model based exclusively on SD (Lönnstedt, 1983). Drawing on this work, models were developed to assess national-level policies, first at IIASA, but later also at the European Forest Institute and several European universities. These include SPE models for Austria (Schwarzbauer, 1990), Finland (Ronnila, 1995), Norway (Trømborg and Solberg, 1995) and the European Union (Kallio, Moiseyev, and Solberg 2004), and SD models for Austria (Schwarzbauer, 1990), Sweden (Lonnstedt, 1986) and Eastern France (Lönnstedt and Peyron, 1989). European outlook studies have been performed since 1952 by the FAO/ UNECE. They mostly rely on econometric models (e.g. Baudin, 1995; Jonsson, 2012; Kangas and Baudin, 2003), but have recently turned to using FSM as well. The sixth outlook study, EFSOS (FAO, 2005), used EFISCEN[13], and the seventh, EFSOS II (FAO, 2010), a model developed by the European Forest Institute.

3.4. Current research is still shaped by early developments

As outlined above, models developed in the 1990-2010 period have largely relied on previous efforts. Since reviews by Caurla (2013) and Latta et al. (2013), this trend in model filiation has continued. Most models cited above are still used in updated forms (e.g. Beach and McCarl, 2010; Buongiorno and Zhu, 2017; Favero et al., 2018; Galik et al., 2015; Kallio and Solberg, 2018; Kallio et al., 2016; 2018), with the exception of SD models, rarer today (Schwarzbauer *et al.*, 2013; Stern *et al.*, 2015). New SPE models include the Scandinavian NFSM (Mustapha, 2016), the global RPFTM (Johnston and van Kooten, 2016; Sun and Bogdanski, 2017) and GFTM models (Jonsson *et al.*, 2016), while STIMM is a Swedish timber supply optimisation model

[12] Samuelson's SPE framework had also been used for models of the agricultural sector from the 1970s, both in the US and at IIASA (Baumes, 1978; McCarl and Spreen, 1980; NORTON and SCHIEFER, 1980).
[13] EFISCEN focuses on natural dynamics in forests and on timber harvests, but demand is exogenous and timber industries are not represented. Hence, it can be considered a large scale forest simulator rather than forest sector model in a strict sense.

(Gong, Löfgren and Rosvall, 2013; Guo and Gong, 2017a), and several regional models were developed for Canadian provinces (Niquidet and Friesen, 2014; Peter and Niquidet, 2016). Other recent models are not directly sourced from their older counterparts, but still show resemblances. The French FFSM (Caurla *et al.*, 2010) was developed using a IIASA-inspired recursive framework, but includes a detailed description of forest resources as found in SM models. This indirect filiation was reinforced in the later FFSM++ model (Lobianco, Delacote, *et al.*, 2016), where forest investment was made endogenous by adding an optimal harvest scheduling module based on Faustmann (1849). Another recent model is LURA for the USA (Gregory S. Latta, Baker and Ohrel, 2018). Like SPE models, it is recursive, uses mathematical programming to solve static optimisation problems, and the objective function includes transport costs. However, it has a detailed description of forest resources and focuses on optimally allocating supply from various locations to meet an exogenous domestic demand, drawing a parallel to SM models.

These cross-influences in model development have benefited from FSM developing within a small research field. For example, the Global Forest Sector project at IIASA was partly financed by the US Forest Service and the FAO, and included visits by scholars involved in the development of other models for the RPA assessment system or at RFF (e.g. J.Buongiorno, K.Gilles, K.Lyon, R.Sedjo)[14]. More recently, the Norwegian NorFor model was developed by researchers involved with a recursive model derived from work at IIASA on the one hand, and others participating in building intertemporal models in the US on the other hand. As a result, NorFor integrates aspects of both approaches (Sjølie *et al.*, 2015a). This structuration of the research field along historical teams can be witnessed in Figure 1, where clusters generally correspond to either one model or to several models with strong historical ties. Across clusters, scholars involved in models sharing historical ties display higher levels of relatedness, for example G.Latta and H.Sjølie, or B.Solberg, E.Trømborg and T.F. Bolkesjø. The same is true of scholars having developed models with similar approaches. The other major divide is between scholars belonging to research teams based in North-America, and those located in Europe. As we discuss in section 4, the fact that FSM have an applied use in decision support conditions a large part of modelling activities. Hence, it is not surprising that the bibliographic coupling metric highlights the geographical clustering of the field, even when models do not belong to the same historical "family" (e.g. EUFASOM and EFI-GTM). In such instances, relatedness is due to proximity in policy-relevance.

4. Facts representation in FSM is conditioned by their applied purpose for decision support

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

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

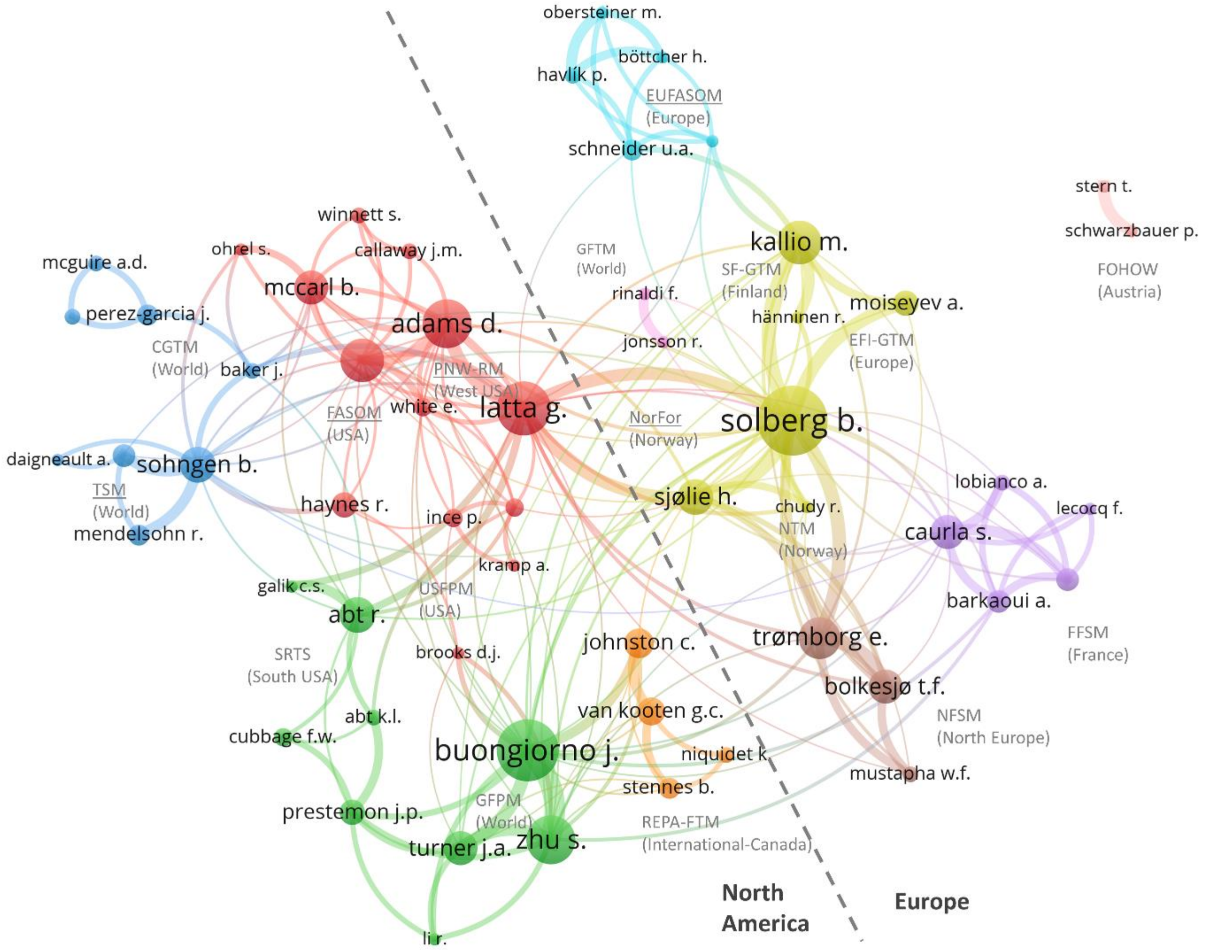

Figure 1.1 - Bibliographic network of scholars in the FSM field, based on bibliographic coupling. Data was retrieved from Scopus database in July 2019 following the methodology used in Riviere et al. (2020). A bibliographic-coupling link is formed when two publications share common references. The size of items is proportional to the number of papers each scholar has authored, distances between items indicates their level of relatedness, and colours correspond to clusters based on item relatedness. Model names have been added manually based on authors' knowledge. Models whose names are underlined are intertemporal optimisation models, others are recursive models. For visibility purposes, only scholars with at least 3 papers are shown. The network was generated using VosViewer (van Eck and Waltman, 2010) software.

4.1. Model building and the "external dynamics" are heavily influenced by policy debates

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

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

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

New technologies have been added as input-output processes to represent bioenergy production (e.g. Folsland Bolkesjø et al., 2006) and carbon accounting modules have been developed to account for carbon sequestration (e.g. Lobianco et al., 2016a; Wear and Coulston, 2019).

4.2. Facts are incorporated into narratives forming the base for scenario analysis and simulations

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

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

The experimental interaction with models is also standard, and falls within what Morgan calls "experiments in the world of the model"[15] (Morgan, 2012, 258-271). However, simulations provide information beyond numerical results: they enable assessing the transmission of economic signals throughout the forest sector, isolating and highlighting the determinants of

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

a mechanism in that complex system, and assessing the sensitivity of a mechanism to its determinants. To do so, forest sector modellers run several simulations where parameter values vary and, more recently, some have turned to sensitivity analysis methods such as Monte-Carlo simulations (e.g. Buongiorno and Johnston, 2018; Kallio, 2010). In doing so, they add variability to the experiment, which is necessary because FSM are largely deterministic models, and perform the necessary "active collusion" described by Morgan[16]. FSM simulations then constitute an "instrument of observation of the world in the model" (Morgan 2012, 331) by revealing hidden structures and enabling their investigation under impulsions from the user. Morgan's analysis then corroborates Solberg's early intuition of FSM as exploration tools for scientific enquiry, illustrated in his writing that FSM helps scientists understand "what are the most essential relations to explore more in detail empirically and theoretically" (Solberg, 1986, 425).

5. Concluding remarks: going forward with forest sector models

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

Even though the activity of model developers may be partly oriented by policy debates, choosing and building models remains a critical step on which researchers have agency, and knowledge of the determinants behind modelling practices can only benefit the research community. FSM have known 50 years of continued development and successive improvements through an iterative process. Many methods have been inherited from past efforts, and exchanges across research teams have happened on several occasions. As we have seen, the context of model development, local specificities as well as methods and data available at the time can all be important determinants in shaping models. For these reasons, modellers involved in new research should be encouraged to research the history of their field in order to better understand the whys and wherefores of modelling practices, to adopt the best approaches and to adapt or improve them when necessary. On the other hand, modellers should also be encouraged to disclose and explain the reasons that have led to their modelling choices, and to discuss the constraints they have faced. Current publishing formats may not always enable it, and technical documents can be published in such cases.

A good understanding of such information enables the choice of appropriate modelling methods. As we have seen, several modelling paradigms exist, each with different underlying assumptions. Models based on intertemporal or static-recursive optimisation may not only yield different results, but also behave differently to similar stimuli (Sohngen and Sedjo, 1998; Sjølie *et al.*, 2015a). Even within one modelling framework, changing assumptions on agent behaviours has a similar potential to alter results for a given scenario (Hanne K. Sjølie *et al.*, 2011; Lobianco, Delacote, *et al.*, 2016). The sensitivity of model results to assumptions regarding the target's functioning not only concerns economic behaviours, but also natural dynamics such as forest growth and carbon sequestration, where bias can be introduced depending on the methods chosen for representation (Wear and Coulston, 2019). In addition, research also depends on the availability and quality of the empirical data used to calibrate

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

models (Kallio et al. 2018; Buongiorno and Johnston 2018). In all these cases, different results may tell different stories, potentially affecting decision-making, especially when expertise is explicitly required, and it is important for modellers to be aware of such implications when choosing how to model facts. Besides, one should also keep in mind the limitations of these choices when interpreting results and moving from science to expertise, which is often the case with FSM.

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

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

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

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

References

Adams, Darius M., Ralph J. Alig, Jack M. Callaway, Steven M. Winnett, and Bruce A. McCarl. 1996. *The Forest and Agricultural Sector Optimization Model (FASOM): Model Structure and Policy Applications*. Darby: Diane Publishing.

Adams, Darius M, and Gregory S Latta. 2005. Costs and Regional Impacts of Restoration Thinning Programs on the National Forests in Eastern Oregon. *Canadian Journal of Forest Research*, *35*(6):1319-1330.

Adams, Darius M., and Richard W. Haynes. 2007. *Resource and Market Projections for Forest Policy Development: Twenty-five Years of Experience with the US RPA Timber Assessment (Vol. 14)*. Dordrecht: Springer Science & Business Media.

Alston, Richard Moss. 1972. *FOREST: Goals and Decisionmaking in the Forest Service (Vol. 128)*. Intermountain Forest & Range Experiment Station, Forest Service, US Department of Agriculture.

Amacher, Gregory, Markku Ollikainen, and Erkki Koskela. 2010. *Economics of Forest Resources*. Cambridge: The MIT Press.

Armatte, Michel. 2007. Les économistes face au long terme : l'ascension de la notion de scénario. In Amy Dahan (dir.), *Les Modèles du Futur*, 63-90. Paris: La Découverte.

Attocchi, Giulia. 2015. *Silviculture of Oak for High-Quality Wood Production - Effects of Thinning on Crown Size, Volume Growth and Stem Quality in Even-Aged Stands of Pedunculate Oak (Quercus Robur L.) in Northern Europe*. Alnarp : Sveriges lantbruksuniv., Acta Universitatis Agriculturae Sueciae.

Bataille, Chris, Henri Waisman, Michel Colombier, Laura Segafredo, and Jim Williams. 2016. The Deep Decarbonization Pathways Project (DDPP): Insights and emerging issues. *Climate Policy*, *16*(suppl. 1): 1-6.

Baudin, Anders, and David Brooks. 1995. Projections of Forest Products Demand, Supply and Trade. *ETTS V Working Papers*. Geneva: United Nations.

Baumes, Harry Stevens. 1978. *A Partial Equilibrium Sector Model of US Agriculture Open to Trade: A Domestic Agricultural and Agricultural Trade*. West Lafayette: Purdue University.

Beach, Robert H., and Bruce A. McCarl. 2010. *US Agricultural and Forestry Impacts of the Energy Independence and Security Act: FASOM Results and Model Description*. Research Triangle Park: RTI International.

Bengston, David N., Stanley T. Asah, and Brett J. Butler. 2011. The Diverse Values and Motivations of Family Forest Owners in the United States: An Analysis of an Open-Ended Question in the National Woodland Owner Survey. *Small-Scale Forestry*, *10*(3): 339-355.

Böhringer, Christoph. 2014. Two Decades of European Climate Policy: A Critical Appraisal. *Review of Environmental Economics and Policy*, *8*(1): 1-17.

Bolkesjø, Torjus, Erik Trømborg, and Birger Solberg. 2006. Bioenergy from the Forest Sector: Economic Potential and Interactions with Timber and Forest Products Markets in Norway. *Scandinavian Journal of Forest Research*, *21*(2): 175-185.

Bowes, Michael D, and John V. Krutilla. 1985. Multiple Use Management of Public Forestlands. In A. V. Kneese and J. L. Sweeney (eds), *Handbook of Natural Resource and Energy Economics (Vol. 2)*, 531-569. Amsterdam: Elsevier Science.

Bowes, Michael D, and John V Krutilla. 1989. *Multiple-Use Management: The Economics of Public Forestlands*. Washington DC: Ressources For the Future.

Brockerhoff, Eckehard G., Luc Barbaro, Bastien Castagneyrol, David I. Forrester, Barry Gardiner, José Ramón González-Olabarria, Phil O. B. Lyver, et al. 2017. Forest Biodiversity, Ecosystem Functioning and the Provision of Ecosystem Services. *Biodiversity and Conservation*. Amsterdam: Springer Netherlands.

Buongiorno, Joseph. 1996. Forest Sector Modeling: A Synthesis of Econometrics, Mathematical Programming, and System Dynamics Methods. *International Journal of Forecasting*, *12*(3): 329-343.

Buongiorno, Joseph. 2014. Global Modelling to Predict Timber Production and Prices: The GFPM Approach. *Forestry*, *88*(3): 291-303.

Buongiorno, Joseph, and Craig Johnston. 2018. Effects of Parameter and Data Uncertainty on Long-Term Projections in a Model of the Global Forest Sector. *Forest Policy and Economics*, *93*(May): 10-17.

Buongiorno, Joseph, Craig Johnston, and Shushuai Zhu. 2017. An Assessment of Gains and Losses from International Trade in the Forest Sector. *Forest Policy and Economics*, *80*: 209-217.

Buongiorno, Joseph, and Shushuai Zhu. 2017. Potential Effects of a Trans-Pacific Partnership on Forest Industries. *Forest Policy and Economics*, *81*: 97-104.

Buongiorno, Joseph, Shushuai Zhu, Dali Zhang, James Turner, and David Tomberlin. 2003. GFPM Structure and Formulation. In *The Global Forest Products Model*, 39-55. San Diego: Academic Press.

Caurla, Sylvain. 2013. Une typologie et une histoire des modèles économiques de secteur forestier. *Revue Forestière Française*, *65*(2): 163-181.

Caurla, Sylvain. 2014. Le Modèle FFSM 1.0 : De l'outil de recherche en économie à son utilisation pour l'aide à la décision. *Revue Forestière Française*, *66*(3): 313-324.

Caurla, Sylvain, Vincent Bertrand, Philippe Delacote, and Elodie Le Cadre. 2018. Heat or Power: How to Increase the Use of Energy Wood at the Lowest Cost? *Energy Economics*, *75*(September): 85-103.

Caurla, Sylvain, Philippe Delacote, Franck Lecocq, Julien Barthès, and Ahmed Barkaoui. 2013. Combining an Inter-Sectoral Carbon Tax with Sectoral Mitigation Policies: Impacts on the French Forest Sector. *Journal of Forest Economics*, *19*(4): 450-461.

Caurla, Sylvain, Franck Lecocq, Philippe Delacote, and Ahmed Barkaoui. 2010. The French Forest Sector Model: Version 1.0. *Document de Travail Du LEF,* N°2010-04. Nancy: AgroParisTech, INRA.

Costanza, Jennifer K., Robert C. Abt, Alexa J. McKerrow, and Jaime A. Collazo. 2017. Bioenergy Production and Forest Landscape Change in the Southeastern United States. *GCB Bioenergy*, *9*(5): 924-939.

D'amours, Sophie, Mikael Rönnqvist, and Andres Weintraub. 2008. Using Operational Research for Supply Chain Planning in the Forest Products Industry. *INFOR*, *46*(4): 265-281.

Daigneault, Adam, Craig Johnston, Anu Korosuo, Justin S Baker, Nicklas Forsell, Jeffrey Prestemon, and Robert C Abt. 2019. Developing Detailed Shared Socioeconomic Pathway (SSP) Narratives for the Global Forest Sector. *Journal of Forest Economics*, *34*(1-2): 7-45.

Dantzig, G.B. (1951) Application of the Simplex Method to a Transportation Problem, *Activity Analysis of Production and Allocation. Koopmans*, T.C., Ed., John Wiley and Sons, New York, 359-373.
Dantzig, George B., Nicholas Georgescu-Roegen, Paul A. Samuelson, and Albert W. Tucker. 1951. *Activity Analysis of Production and Allocation: Proceedings of a Conference*. New York: Wiley & Sons.
Devadoss, Stephen, Angel H. Aguiar, Steven R. Shook, and Jim Araji. 2005. A Spatial Equilibrium Analysis of U.S.-Canadian Disputes on the World Softwood Lumber Market. *Canadian Journal of Agricultural Economics*, *53*(2-3): 177-192.
Du Monceau, Duhamel. 1764. *De l'exploitation des bois, ou moyens de tirer un parti auantageux des taillis, demi-futaies et hautes-futaies, et d'en faire une juste estimation: avec la description des Arts qui se pratiquent dans les forets: faisant partie du Traité complet des bois & des forests. Par M. Duhamel du Monceau (Vol. 1)*. Paris: H. L. Guerin & L. F. Delatour.
Duloy, John H, and Roger D Norton. 1975. Prices and Incomes in Linear Programming Models. *American Journal of Agricultural Economics*, *57*(4): 591-600.
Eck, Nees Jan van, and Ludo Waltman. 2010. Software Survey: VOSviewer, a Computer Program for Bibliometric Mapping. *Scientometrics*, *84*(2): 523-538.
Eriksson, Mathilda. 2015. The Role of the Forest in an Integrated Assessment Model of the Climate and the Economy. *Climate Change Economics*, *6*(3): 1-29.
European Commission. 2016. *Proposal for a Regulation of the European Parliament and of the Council for the Inclusion of GHG Emissions and Removals from LULUCF into the 2030 Climate and Energy Framework*.
European Commission. 2017. *Proposal for a Directive of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources*.
European Parliament, and European Council. 2018. *Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the Inclusion of Greenhouse Gas Emissions and Removals From Land Use, Land Use Change and Forestry in the 2030 Climate and Energy Framework*.
Eurostat. 2019. Agriculture, forestry and fishery statistics, 2019 edition. Luxembourg: Eurostat.
FAO, UNECE. 2005. *European Forest Sector Outlook Study*. Geneva: United Nations.
FAO, UNECE. 2010. *The European Forest Sector Outlook Study II*. Geneva: United Nations.
Faustmann, Martin. 1849. Berechnung Des Wertes Welchen Wladboden Sowie Noch Nicht Haubare Holzbestände Für Die Wladwirtschaft Besitzen [Calculation of the Value Which Forest Land and Immature Stands Possess for Forestry]. *Allgemeine Forst-Und Jadg-Zeitung 15*: 441-455.
Favero, Alice, Robert Mendelsohn, and Brent Sohngen. 2017. Using Forests for Climate Mitigation: Sequester Carbon or Produce Woody Biomass? *Climatic Change*, *144*(2): 195-206.
Favero, Alice, Robert Mendelsohn, and Brent Sohngen. 2018. Can the Global Forest Sector Survive 11°C Warming? *Agricultural and Resource Economics Review*, *47*(2): 388-413.
Fenille, Phillibert Charles Marie (de). 1791. *Observations Sur l'aménagement des forêts, et particulièrement des forêts nationales*. Paris: Société Royale d'Agriculture.
Ficko, Andrej, Gun Lidestav, Áine Ní Dhubháin, Heimo Karppinen, Ivana Zivojinovic, and Kerstin Westin. 2019. European Private Forest Owner Typologies: A Review of Methods and Use. *Forest Policy and Economics*, *99*(February): 21-31.
Folsland Bolkesjø, Torjus, Erik Trømborg, and Birger Solberg. 2006. Bioenergy from the Forest Sector: Economic Potential and Interactions with Timber and Forest Products Markets in Norway. *Scandinavian Journal of Forest Research*, *21*(2): 175-185.
Forrester, Jay W. 1969. *Urban Dynamics*. Cambridge: MIT Press.
Fortes, Patrícia, António Alvarenga, Júlia Seixas, and Sofia Rodrigues. 2015. Long-Term Energy Scenarios: Bridging the Gap between Socio-Economic Storylines and Energy Modeling. *Technological Forecasting and Social Change*, *91*(February): 161-178.
Frigg, Roman, and James Nguyen. 2017. Models and Representation. In L. Magnani and T. Bertolotti (eds), *Springer Handbook of Model-Based Science*, 49-102. Cham: Springer.
Galik, Christopher S., and Robert C. Abt. 2016. Sustainability Guidelines and Forest Market Response: An Assessment of European Union Pellet Demand in the Southeastern United States. *GCB Bioenergy*, *8*(3): 658-669.
Galik, Christopher S., Robert C. Abt, Gregory Latta, and Tibor Vegh. 2015. The Environmental and Economic Effects of Regional Bioenergy Policy in the Southeastern U.S. *Energy Policy*, *85*(October): 335-346.
Gelfert, Axel. 2017. The Ontology of Models. In L. Magnani
Gilless, J Keith, and Joseph Buongiorno. 1985. *PELPS: Price-Endogenous Linear Programming System for Economic Modeling.* Research Division of the College of Agricultural and Life Sciences. Madison: University of Wisconsin Press.
Gong, Peichen, Karl Gustaf Löfgren, and Ola Rosvall. 2013. Economic Evaluation of Biotechnological Progress: The Effect of Changing Management Behavior. *Natural Resource Modeling*, *26*(1): 26-52.
Gräbner, Claudius. 2018. How to Relate Models to Reality? An Epistemological Framework for the Validation and Verification of Computational Models. *Journal of Artificial Societies and Social Simulation*, *21*(3).
Graves, Henry S. 1934. A National Plan for American Forestry. *Geographical Review*, *24*(1): 129-133.
Gunderson, Kari, and Alan Watson. 2007. Understanding Place Meanings on the Bitterroot National Forest, Montana. *Society and Natural Resources*, *20*(8): 705-721.
Guo, Jinggang, and Peichen Gong. 2017. The Potential and Cost of Increasing Forest Carbon Sequestration in Sweden. *Journal of Forest Economics*, *29*(December): 78-86.
Gupta, Joyeeta. 2010. A History of International Climate Change Policy. *Wiley Interdisciplinary Reviews: Climate Change*, *1*(5): 636-653.
Hamilton, Serena H., Sondoss Elsawah, Joseph H. A. Guillaume, Anthony J. Jakeman, and Suzanne A. Pierce. 2015. Environmental Modelling & Software Integrated Assessment and Modelling : Overview and Synthesis of Salient Dimensions. *Environmental Modelling and Software*, *64*(February): 215-229.
Baudrillart, J. J. 1805. Instruction sur la culture du bois, à l'usage des forestiers: Ouvrage traduit de l'allemand de GI Hartig, Mattre des Forêts de la principauté de Solms, et Membre honoraire de la Société de physique de Berlin. Paris: Levrault.
Hartman, Richard. 1976. The Harvesting Decision When a Standing Forest Has Value. *Economic Inquiry*, *14*(March): 52-58.

Haug, Constanze, and Joyeeta Gupta. 2013. The Emergence of REDD on the Global Policy Agenda. In O. Kuik, J. Gupta, N. van der Grijp (eds), *Climate Change, Forests and REDD: Lessons for Institutional Design*, 77-98. Abingdon: Routledge.
Hetemäki, Lauri, and Elias Hurmekoski. 2016. Forest Products Markets under Change: Review and Research Implications. *Current Forestry Reports*, *2*(3): 177-188.
Hotelling, Harold. 1931. The Economics of Exhaustible Resources. *Journal of Political Economy*, *39*(2): 137-175.
Hough, Franklin B. 1878. *Report upon Forestry*. Washington, DC: Government Printing Office
Hujala, Teppo, Tanja Laitila, Mikko Kurttila, and Jukka Tikkanen. 2004. Multiple Motives of Family Forest Owners in Their Speech about Forest-Related Decision-Making. *Proceedings of the Biennial Meeting of the Scandinaviant Society of Forest Economics*, (40): 335-343.
Hurmekoski, Elias, and Lauri Hetemäki. 2013. Studying the Future of the Forest Sector: Review and Implications for Long-Term Outlook Studies. *Forest Policy and Economics*, *34*(C): 17-29.
Hurmekoski, Elias, and Hanne K. Sjølie. 2018. Comparing Forest Sector Modelling and Qualitative Foresight Analysis: Cases on Wood Products Industry. *Journal of Forest Economics*, *31*(April): 11-16.
Hyde, William F. 1980. *Timber Supply, Land Allocation, and Economic Efficiency*. New York: Routledge.
Ince, Peter J., Andrew D. Kramp, Kenneth E. Skog, Henry N. Spelter, David N. Wear, Peter J. 2011. *U.S. Forest Products Module: A Technical Document Supporting the Forest Service 2010 RPA Assessment*. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
IPCC. 1990. *Climate Change: The IPCC Scientific Assessment.* Cambridge: Cambridge University Press.
IPCC. 1996. *Climate Change 1995: The Science of Climate Change*. Cambridge: Cambridge University Press.
Johnston, Craig M. T., and G. Cornelis van Kooten. 2014. Economic Consequences of Increased Bioenergy Demand. *Forestry Chronicle*, *90*(5): 636-642.
Johnston, Craig M. T., and G. Cornelis van Kooten. 2016. Global Trade Impacts of Increasing Europe's Bioenergy Demand. *Journal of Forest Economics*, *23*(April): 27-44.
Johnston, Craig M. T., and G. Cornelis van Kooten. 2017. Impact of Inefficient Quota Allocation under the Canada-U.S. Softwood Lumber Dispute: A Calibrated Mixed Complementarity Approach. *Forest Policy and Economics*, *74*(January): 71-80.
Johnston, Craig M. T., and Rajan Parajuli. 2017. What's next in the U.S.-Canada Softwood Lumber Dispute? An Economic Analysis of Restrictive Trade Policy Measures. *Forest Policy and Economics*, *85*(December): 135-146.
Jonsson, Ragnar. 2012. Econometric Modelling and Projections of Wood Products Demand, Supply and Trade in Europe. *Geneva Timber And Forest Discussion Paper 59*. Geneva: United Nations.
Jonsson, Ragnar, Francesca Rinaldi, Minna Räty, and Ola Sallnäs. 2016. Integrating Forest-Based Industry and Forest Resource Modeling. *IForest*, *9*(5): 743-750.
Kallio, A. Maarit I. 2010. Accounting for Uncertainty in a Forest Sector Model Using Monte Carlo Simulation. *Forest Policy and Economics*, *12*(1): 9-16.
Kallio, A. Maarit I., Riitta Hänninen, Nina Vainikainen, and Sandra Luque. 2008. Biodiversity Value and the Optimal Location of Forest Conservation Sites in Southern Finland. *Ecological Economics*, *67*(2): 232-243.
Kallio, A. Maarit I, Olli Salminen, and Risto Sievänen. 2016. Forests in the Finnish Low Carbon Scenarios. *Journal of Forest Economics*, *23*(April): 45-62.
Kallio, A. Maarit I, and Birger Solberg. 2018. Leakage of Forest Harvest Changes in a Small Open Economy: Case Norway. *Scandinavian Journal of Forest Research*, *33*(5): 502-510.
Kallio, A., Birger Solberg, A. Maarit I. Kallio, and Birger Solberg. 2018. On the Reliability of International Forest Sector Statistics: Problems and Needs for Improvements. *Forests*, *9*(7): 407.
Kallio, A. Maarit I., Alexander Moiseyev, and Birger Solberg. 2004. The Global Forest Sector Model EFI-GTM. The Model Structure. *Joensuu: the European Forest Institute.*
Kallio, A Maarit I, Birger Solberg, Liisa Käär, and Risto Päivinen. 2018. Economic Impacts of Setting Reference Levels for the Forest Carbon Sinks in the EU on the European Forest Sector. *Forest Policy and Economics*, *92*(May): 193-201.
Kallio, Markku, Dennis P. Dykstra, and Clark S. Binkley. 1987. *The Global Forest Sector: An Analytical Perspective*. New York: John Wiley and Sons
Kangas, Kari, and Anders Baudin. 2003. *Modelling and Projections of Forest Products Demand, Supply and Trade in Europe (Vol. 30)*. New York and Geneva: United Nations.
Koopmans, Tjalling C. 1949. Optimum Utilization of the Transportation System. *Econometrica*, *17*(July): 136-146.
Koopmans, Tjalling C. 1951. Activity Analysis of Production and Allocation. In *Cowles Commission for Research Economics, Monograph 13*. Chicago: The University of Chicago. 406-414.
Kooten, G. Cornelis van, and Craig Johnston. 2014. Global Impacts of Russian Log Export Restrictions and the Canada-U.S. Lumber Dispute: Modeling Trade in Logs and Lumber. *Forest Policy and Economics*, *39*(February): 54-66.
Latta, Gregory S., Justin S. Baker, and Sara Ohrel. 2018. A Land Use and Resource Allocation (LURA) Modeling System for Projecting Localized Forest CO2 effects of Alternative Macroeconomic Futures. *Forest Policy and Economics*, *87*(October): 35-48.
Latta, Gregory S., Hanne K. Sjolie, and Birger Solberg. 2013. A Review of Recent Developments and Applications of Partial Equilibrium Models of the Forest Sector. *Journal of Forest Economics*, *19*(4): 350-360.
Lauri, Pekka, Nicklas Forsell, Mykola Gusti, Anu Korosuo, Petr Havlík, and Michael Obersteiner. 2019. Global Woody Biomass Harvest Volumes and Forest Area Use Under Different Global Woody Biomass Harvest Volumes and Forest Area Use Under Different SSP-RCP Scenarios. *Journal of Forest Economics*, *34*(November): 285-309.
Lauri, Pekka, Maarit Kallio, and Uwe A. Schneider. 2013. The Future Development of the Use of Wood in Russia and Its Potential Impacts on the EU Forest Sector. *Scandinavian Journal of Forest Research*, *28*(3): 291-302.
Lecocq, Franck, Sylvain Caurla, Philippe Delacote, Ahmed Barkaoui, and Alexandre Sauquet. 2011. Paying for Forest Carbon or Stimulating Fuelwood Demand? Insights from the French Forest Sector Model. *Journal of Forest Economics*, *17*(2): 157-168.

Lenglet, Jonathan. 2018. Réorganisation institutionnelle et recomposition territoriale de la filière forêt-bois française : exemples du Grand-Est et de la Franche-Comté. *Annales de Géographie*, *721*(3): 254-278.
Li, Yanshu, Bin Mei, and Thaís Linhares-Juvenal. 2019. The Economic Contribution of the World's Forest Sector. *Forest Policy and Economics*, *100*(March): 236-253.
Lobianco, Antonello, Sylvain Caurla, Philippe Delacote, and Ahmed Barkaoui. 2016. Carbon Mitigation Potential of the French Forest Sector under Threat of Combined Physical and Market Impacts Due to Climate Change. *Journal of Forest Economics*, *23*(April): 4-26.
Lobianco, Antonello, Philippe Delacote, Sylvain Caurla, and Ahmed Barkaoui. 2015. The Importance of Introducing Spatial Heterogeneity in Bio-Economic Forest Models: Insights Gleaned from FFSM++. *Ecological Modelling*, *309-310*(August): 82-92.
Lobianco, Antonello, Philippe Delacote, Sylvain Caurla, and Ahmed Barkaoui. 2016. Accounting for Active Management and Risk Attitude in Forest Sector Models: An Impact Study on French Forests. *Environ Model Assess*, 21: 391–405.
Lonnstedt, L. 1986. A Dynamic Forest Sector Model with a Swedish Case. *Forest Science*, *32*(2): 377-397.
Lönnstedt, Lars. 1983. A Forest Sector Prototype Model - The Simplified Model Structure. *IIASA Working Paper*, Laxenburg: IIASA.
Lönnstedt, Lars, and Jean-Luc Peyron. 1989. FIBRE : A French PC-Based Regional Forest Sector Model Applied to Burgundy. *Annales des Sciences Forestières*. *46*(2): 101-118.
Lyon, Kenneth S., and Roger A. Sedjo. 1983. An Optimal Control Theory Model to Estimate the Regional Long- Term Supply of Timber. *Forest Science*, *29*(4): 798-812.
Lyon, Kenneth S. 1981. Mining of the Forest and the Time Path of the Price of Timber. *Journal of Environmental Economics and Management*, *8*(4): 330-344.
Lyon, Kenneth S, and Roger A Sedjo. 1986. Theory Version of ECHO. *Forest Sci* (Vol. 32).
Maas, Harro. 2014. *Economic Methodology: A Historical Introduction*. London: Routledge.
Matarasso, Pierre. 2007. La construction historique des paradigmes de modélisation intégrée: William Nordhaus, Alan Manne et l'apport de la Cowles Commission. In Amy Dahan (ed.), *Les Modèles du Futur*, 44-62. Paris: La Découverte.
McCarl, Bruce A., and Thomas H. Spreen. 1980. Price Endogenous Mathematical Programming as a Tool for Sector Analysis. *American Journal of Agricultural Economics*, *62*(1): 87-102.
Meadows, Donella H., Dennis L. Meadows, Jorgen Randers, and William W. Behrens. 1972. *The Limits to Growth. A Report for the Club of Rome's Project on the Predicament of Mankind. New York: Universe Books.*
McKillop, W. L. M. 1967. Supply and Demand for Forest Products—an Econometric Study. *Hilgardia*, *38*(1): 1-132.
Moiseyev, Alexander, Birger Solberg, and A. Maarit I. Kallio. 2014. The Impact of Subsidies and Carbon Pricing on the Wood Biomass Use for Energy in the EU. *Energy*, *76*(C): 161-167.
Moiseyev, Alexander, Birger Solberg, A. Maarit I. Kallio, and Marcus Lindner. 2011. An Economic Analysis of the Potential Contribution of Forest Biomass to the EU RES Target and Its Implications for the EU Forest Industries. *Journal of Forest Economics*, *17*(2): 197-213.
Moiseyev, Alexander, Birger Solberg, Bruce Michie, and A. Maarit I. Kallio. 2010. Modeling the Impacts of Policy Measures to Prevent Import of Illegal Wood and Wood Products. *Forest Policy and Economics*, *12*(1): 24-30.
Morgan, Mary S. 2012. *The World in the Model: How Economists Work and Think*. Cambridge: Cambridge University Press.
Morgan, Mary S., and Tarja Knuuttila. 2012. Models and Modelling in Economics. In Uskali Mäki (ed.), *Philosophy of Economics*, 49-87. Amsterdam: North Holland.
Mustapha, W. F., E. Trømborg, and T. F. Bolkesjø. 2017. Forest-Based Biofuel Production in the Nordic Countries: Modelling of Optimal Allocation. *Forest Policy and Economics*: 1-10.
Mustapha, Walid. 2016. *The Nordic Forest Sector Model (NFSM): Data and Model Structure*. Ås: Norwegian University of Life Sciences.
Nambiar, E. K. Sadanandan. 2019. Re-Imagining Forestry and Wood Business: Pathways to Rural Development, Poverty Alleviation and Climate Change Mitigation in the Tropics. *Forest Ecology and Management*, *448*(September): 160-173.
Niquidet, Kurt, and Devon Friesen. 2014. Bioenergy Potential from Wood Residuals in Alberta: A Positive Mathematical Programming Approach. *Canadian Journal of Forest Research*, *44*(12): 1586-1594.
Northway, Steven, Gary Q. Bull, and John D. Nelson. 2013. Forest Sector Partial Equilibrium Models: Processing Components. *Forest Science*, *59*(2): 151-156.
Norton, Roger., and gerhard W. Schiefer. 1980. Agricultural Sector Programming Models: A Review. *European Review of Agricultural Economics*, *7*(3): 229-265.
Pearce, David. 2002. An Intellectual History of Environmental Economics. *Annual Review of Energy and the Environment*, *27*: 57-81.
Perez-Garcia, John, Linda A. Joyce, Clark S. Binkley, and Andrew D. McGuire. 1997. Economic Impacts of Climatic Change on the Global Forest Sector: An Integrated Ecological/Economic Assessment. *Critical Reviews in Environmental Science and Technology*, *27*(suppl.): 123-138.
Peter, Brian, and Kurt Niquidet. 2016. Estimates of Residual Fibre Supply and the Impacts of New Bioenergy Capacity from a Forest Sector Transportation Model of the Canadian Prairie Provinces. *Forest Policy and Economics*, *69*(August): 62-72.
Peyron, J. L. 1999. Les fondements de l'économie forestière moderne: le rôle capital de Faustmann, Il y a 150 ans, et celui de quelques-uns de ses précurseurs et successeurs. *Revue Forestiere Francaise*, *51*(6): 679-698.
Pohjola, Johanna, Jani Laturi, Jussi Lintunen, and Jussi Uusivuori. 2018. Immediate and Long-Run Impacts of a Forest Carbon Policy—A Market-Level Assessment with Heterogeneous Forest Owners. *Journal of Forest Economics*, *32*(August): 94-105.
Quinet, Alain, Luc Baumstark, and J. Célestin-Urbain. 2009. *La valeur tutélaire du carbone*. Paris: Centre d'Analyse Stratégique.
Rafal, Chudy, Robert C. Abt, Ragnar Jonsson, Jeffrey P. Prestemon, and Frederick W. Cubbage. 2013. Modeling the Impacts of EU Bioenergy Demand on the Forest Sector of the Southeast U.S. *Journal of Energy and Power Engineering*, *7*(6): 1073-1081.

Reed, William J. 1984. The Effects of the Risk of Fire on the Optimal Rotation of a Forest. *Journal of Environmental Economics and Management*, *11*(2): 180-190.
Riviere, Miguel, Sylvain Caurla, and Philippe Delacote. 2020. Evolving Integrated Models From Narrower Economic Tools: The Example of Forest Sector Models. *Environmental Modeling & Assessment*, *25*: 453-469.
Ronnila, Maarit. 1995. *Medium-Term Scenarios for the Finnish Pulp and Paper Industry*. Laxenburg: IIASA.
Rougieux, Paul, and Olivier Damette. 2018. Reassessing Forest Products Demand Functions in Europe Using a Panel Cointegration Approach. *Applied Economics*, *50*(30): 3247-3270.
Rounsevell, Mark D. A., and Marc J. Metzger. 2010. Developing Qualitative Scenario Storylines for Environmental Change Assessment. *Wiley Interdisciplinary Reviews: Climate Change*, *1*(4): 606-619.
Roux, Alice, Jean-François Dhôte, Claire Bastick, and Antoine Colin. 2017. *Quel rôle pour les forêts et la filière forêt-bois françaises dans l'atténuation du changement climatique ?* Rapport d'étude pour le Ministère de l'agriculture et de l'alimentation, INRA et IGN.
Samuelson, Paul A. 1952. Spatial Price Equilibrium and Linear Programming. *American Economic Review*, *42*(3): 283-303.
Samuelson, Paul A. 1976. Economics of Forestry in an Evolving Society. *Economic Enquiry*, *14*(4): 466-492.
Sauquet, Alexandre, Franck Lecocq, Philippe Delacote, Sylvain Caurla, Ahmed Barkaoui, and Serge Garcia. 2011. Estimating Armington Elasticities for Sawnwood and Application to the French Forest Sector Model. *Resource and Energy Economics*, *33*(4): 771-781.
Schneider, Uwe A., Juraj Balkovic, Stephane de Cara, Oskar Franklin, Steffen Fritz, Petr Havlik, Ingo Huck, et al. 2008. The European Forest and Agricultural Sector Optimization Model - EUFASOM. *16th Annual Conference of the European Association of Environmental and Resource Economists (EAERE),* 25-28 June 2008.
Schwarzbauer, Peter. 1990. Comparison of Two Models of the Austrian Forest Sector. *IIASA Working Paper.* Laxenburg: IIASA
Schwarzbauer, Peter, Stefan Weinfurter, Tobias Stern, and Sebastian Koch. 2013. Economic Crises: Impacts on the Forest-Based Sector and Wood-Based Energy Use in Austria. *Forest Policy and Economics*, *27*(February): 13-22.
Sedjo, Roger A., and Kenneth S. Lyon. 1990. *The Long-Term Adequacy of World Timber Supply*. Washington DC: Resources for the Future.
Sergent, Arnaud. 2010. Régulation politique du secteur forestier en France et changement d'échelle de l'action publique [Political Regulation of the French Forest Sector and Political Rescaling]. *Économie Rurale*, (318-319): 96-110.
Sergent, Arnaud. 2017. Pourquoi la politique forestière française ne veut pas du territoire. *Revue Forestiere Francaise*, *69*(2): 99-109.
Sergent, Arnaud, Bas Arts, and Peter Edwards. 2018. Governance Arrangements in the European Forest Sector: Shifts towards "New Governance" or Maintenance of State Authority? *Land Use Policy*, *79*(December): 968–976.
Shabani, Nazanin, Shaghaygh Akhtari, and Taraneh Sowlati. 2013. Value Chain Optimization of Forest Biomass for Bioenergy Production: A Review. *Renewable and Sustainable Energy Reviews*, *23*(July): 299-311.
Sjølie, Hanne K., Greg S. Latta, and Birger Solberg. 2016. Combining Backcasting with Forest Sector Projection Models to Provide Paths into the Future Bio-Economy. *Scandinavian Journal of Forest Research*, *31*(7): 708-718.
Sjølie, Hanne K., Greg S. Latta, Erik Trømborg, Torjus F. Bolkesjø, and Birger Solberg. 2015. An Assessment of Forest Sector Modeling Approaches: Conceptual Differences and Quantitative Comparison. *Scandinavian Journal of Forest Research*, *30*(1): 60-72.
Sjølie, Hanne K., Gregory S. Latta, Darius M. Adams, and Birger Solberg. 2011. Impacts of Agent Information Assumptions in Forest Sector Modeling. *Journal of Forest Economics*, *17*(2): 169-184.
Smith, Timothy M., Sergio A. Molina Murillo, and Britta M. Anderson. 2013. Implementing Sustainability in the Global Forest Sector: Toward the Convergence of Public and Private Forest Policy. In E. Hansen, R. Panwar, and R. Vlosky (eds), *The Global Forest Sector: Changes, Practices, and Prospects*, 237-260. Boca Raton: CRC Press.
Sohngen, Brent, Robert. Mendelsohn, and Roger Sedjo. 1999. Forest Management, Conservation, and Global Timber Markets. *American Journal of Agricultural Economics*, *81*(1): 1-13.
Sohngen, Brent, and Roger Sedjo. 1998. A Comparison of Timber Market Models: Static Simulation and Optimal Control Approaches. *Forest Science*, *44*(1): 24-36.
Solberg, Birger. 1986. Forest Sector Simulation Models as Methodological Tools in Forest Policy Analysis (Norway). *Silva Fennica*, *20*(4): 419-427.
Solberg, Birger, Alexander Moiseyev, A. Maarit I Kallio, and Anne Toppinen. 2010. Forest Sector Market Impacts of Changed Roundwood Export Tariffs and Investment Climate in Russia. *Forest Policy and Economics*, *12*(1): 17-23.
Solorio, Israel, Helge Jörgens, Israel Solorio, and Pierre Bocquillon. 2017. EU Renewable Energy Policy: A Brief Overview of Its History and Evolution. In I. Solorio and H. Jörgens (eds), *A Guide to EU Renewable Energy Policy*, 23-42. New York: Edward Elgar.
Stedman, Richard C. 2003. Sense of Place and Forest Science: Toward a Program of Quantitative Research. *Forest Science*, *49*(6): 822-829.
Stern, Tobias, Caroline Ledl, Martin Braun, Franziska Hesser, and Peter Schwarzbauer. 2015. Biorefineries' Impacts on the Austrian Forest Sector: A System Dynamics Approach. *Technological Forecasting and Social Change*, *91*(February): 311-326.
Sun, Lili, and Bryan E. C. Bogdanski. 2017. Trade Incentives for Importers to Adopt Policies to Address Illegally Logged Timber: The Case of Non-Tropical Hardwood Plywood. *Journal of Forest Economics*, *27*(April): 18–27.
Swart, R. J., P. Raskin, and J. Robinson. 2004. The Problem of the Future: Sustainability Science and Scenario Analysis. *Global Environmental Change*, *14*(2): 137-146.
Takayama, Takashi, and George G. Judge. 1964a. Spatial Equilibrium and Quadratic Programming. *Journal of Farm Economics*, *46*(1): 67-93.
Takayama, Takashi, and George G. Judge. 1964b. An Interregional Activity Analysis Model for the Agricultural Sector. *Journal of Farm Economics*, *46*(2): 349-365.
Takayama, Takashi, and George G. Judge. 1970. Alternative Spatial Equilibrium Models. *Journal of Regional Science*, *10*(1): 1-12.

Tavoni, Massimo, Brent Sohngen, and Valentina Bosetti. 2007. Forestry and the Carbon Market Response to Stabilize Climate. *Energy Policy*, *35*(11): 5346-5353.
Tomberlin, David, Joseph Buongiorno, and Shushuai Zhu. 1999. *The Global Forest Products Model (GFPM): Users Manual and Guide to Installation*. Department of Forest Ecology and Management. Madison: University of Wisconsin.
Toppinen, Anne, and Jari Kuuluvainen. 2010. Forest Sector Modelling in Europe-the State of the Art and Future Research Directions. *Forest Policy and Economics*, *12*(1): 2-8.
Trømborg, Erik., and Birger Solberg. 1995. Beskrivelse Av En Partiell Likevektsmodell Anvendt I Prosjektet "Modellanalyse Av Norsk Skogsektor" [Description of a Partial Equilibrium Model Applied in the Project 'Model Analysis of Norwegian Forest Sector'] *Ås : Skogforsk.*
Trømborg, Erik, Torjus F. Bolkesjø, and Birger Solberg. 2013. Second-Generation Biofuels: Impacts on Bioheat Production and Forest Products Markets. *International Journal of Energy Sector Management*, *7*(3): 383-402.
US Forest Service. 1958. *Timber Resources for America's Future. Timber Resources for America's Future.* Washington DC : Forest Service, US Department of Agriculture.
US Forest Service. 1965. *Timber Trends in the United States. Timber Trends in the United States.* Washington DC : Forest Service, US Department of Agriculture.
US Forest Service. 1973. *The Outlook for Timber in the United States. The Outlook for Timber in the United States.* Washington DC : Forest Service, US Department of Agriculture.
Hansen, Eric, Rajat Panwar, and Richard Vlosky (eds). 2013. *The Global Forest Sector: Changes, Practices, and Prospects*. Boca Raton: CRC Press.
Wadsworth, Frank H., and John Fedkiw. 2000. Managing Multiple Uses on National Forests, 1905 to 1995: A 90-Year Learning Experience and It Isn't Finished Yet. *Environmental History*, *5*(1): 112-113.
Wear, David N., and John W. Coulston. 2019. Specifying Forest Sector Models for Forest Carbon Projections. *Journal of Forest Economics*, *34*(1-2): 73-97.
Wiersum, K. F., J. L. G. Wong, and H. Vacik. 2018. Perspectives on Non-Wood Forest Product Development in Europe. *International Forestry Review*, *20*(2): 250-262.
Wiesenthal, Tobias, Aphrodite Mourelatou, Jan Erik Petersen, and Peter Taylor. 2006. How Much Bioenergy Can Europe Produce without Harming the Environment? *EEA Report*, *7*(7).
Williams, Gerald W. 2000. *The USDA Forest Service: The First Century (Vol. 650)*. Washington DC: USDA Forest Service.
Woods, Michael. 2013. Regions Engaging Globalization: A Typology of Regional Responses in Rural Europe. *Journal of Rural and Community Development*, *8*(3): 113-126.
Zhu, Shushai, Joseph Buongiorno, and David Tomberlin. 1998. *Global Forest Products Consumption, Production, Trade and Prices: Global Forest Products Model Projections to 2010*. Rome: FAO.

Chapter 2

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

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Abstract

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

1. Introduction

Human societies are today facing a wide array of complex environmental, social and economic challenges at the global scale, including but not restricted to, climatic changes, the erosion of biodiversity and transitioning to low-carbon economies (Diaz et al. 2019; IPCC 2018; Rogelj et al. 2018). Addressing these challenges requires developing a comprehensive but thorough understanding of intricate social-ecological systems in order to perform so-called "integrated assessments". These in turn often rely on "integrated models", which must be able to incorporate ecological, biophysical, economic and social information and dynamics of the systems of interest (Van Delden et al. 2011; Hamilton et al. 2015; Harris 2002). Yet many such models were initially developed with a narrower focus, requiring changes to be made in order to expand the range of analyses possible. Such developments in turn raise questions concerning the suitability of models.

Among ecosystems, forests and forestry play a key role in addressing the above-mentioned issues. Forests cover around 30% of land area globally and provide many market and non-market ecosystem goods and services (Aznar-Sánchez, Belmonte-Ureña, López-Serrano, and Velasco-Muñoz 2018; Brockerhoff et al. 2017). Traditional forest objectives include the production of timber for construction or furniture as well as the manufacturing of paper, which support large industrial sectors. Forestry contributes to climate change mitigation through carbon sequestration (Sedjo and Sohngen 2012) and energy or material substitution (E. Eriksson et al. 2007; Sjølie and Solberg 2011). Forests provide regulation services such as erosion control, water purification, flood regulation and pollination (Broadmeadow and Nisbet 2010; Sturrock et al. 2011) as well as cultural services such as recreation and hunting (Hernández-Morcillo, Plieninger, and Bieling 2013; Milcu et al. 2013). In addition, forests host a large share of the world's biodiversity and harbour key habitats (Hanewinkel, Hummel, and Albrecht 2011). These many goods and services are characterised by complex antagonistic or synergistic relationships at different spatial and temporal scales (Aznar-Sánchez, Belmonte-Ureña, López-Serrano, and Velasco-Muñoz 2018; Garcia, Abildtrup, and Stenger 2018), and while forest management often pursues timber production as its main objective, it also affects the provision of other goods and services (Duncker et al. 2012).

The relationships between multiple forest management objectives have been studied with various methodologies. Traditional forest economics frameworks such as that of the optimal rotation problem (Faustmann 1849) can be extended to account for multiple amenities (Hartman 1976), the joint production of several amenities can be studied by assessing production possibility frontiers (Garcia, Abildtrup, and Stenger 2018), and the provision of multiple ecosystem services can be spatially evaluated with mapping tools (Maes et al. 2012; Tardieu 2017). Several techniques for forest planning have been developed based on group decision making, multi-criteria decision support or public participation (Buchy and Hoverman 2000; Diaz-Balteiro and Romero 2008; Uhde et al. 2015), and forest owners' motives for owning and managing forests can also be analysed using survey methods based on theories in social and behavioural sciences (Ficko et al. 2019). Among these methodologies, Forest sector models (FSM) encompass a set of simulation tools commonly used for policy analysis in the field of forest economics, with a core focus on forecasting developments in timber production and wood products markets (Adams and Haynes 2007; Latta, Sjolie, and Solberg 2013). As coupled bio-economic models of timber markets, forest management and biological dynamics, FSM offer a broad overview of forestry and the forest sector, making them good candidates as integrated models able to "explore the linkages and feedbacks between different system components, including the social, economic and ecological implications of different natural or anthropogenic factors" (Hamilton et al. 2015).

To date, however, there is no detailed, quantitative analysis on how FSM apply to objectives other than the production of timber, in particular environmental objectives. Previous contributions have focused on model theory and development (Adams and Haynes 2007; Buongiorno 2014; Latta, Sjolie, and Solberg 2013; Northway, Bull, and Nelson 2013), or have discussed FSM applications from a broad perspective (Latta, Sjolie, and Solberg 2013; Solberg 1986; Toppinen and Kuuluvainen 2010). The objective of this paper is to fill this gap and investigate how and to what extent forest objectives other than timber production (hereafter, "non-timber objectives") have been studied using FSM. In particular, we aim at demonstrating how a category of originally narrow models focused on economic analysis has gradually evolved to carry out research on environmental questions, and what challenges this trend towards integration implies. Our objective is twofold: first, we seek to identify which non-timber objectives have been studied in FSM research and to what extent. Second, we want to give an overview of research questions over time, and document and question the evolution of modelling approaches. We rely on the combination of two complimentary methods: a systematic literature review and a more in-depth narrative review. This allows us to provide a quantitative overview of the field as well as to focus on specific aspects through examples.

2. Context and review methodology

2.1. Forest Sector Models

FSM are representations of the forest sector based on economic theory. They are mathematical models using sets of equations and mathematical objects to represent a system, as well as simulation models solved numerically due to their large size. They were developed in the 1970s as a new way to project developments in timber markets and have since then been used for policy analysis (Adams and Haynes 2007; Latta, Sjolie, and Solberg 2013; Solberg 1986). We present an overview of FSM focusing on four aspects: the real-world target of FSM, their spatial format, their handling of temporal dynamics, and their objective function.

The real-world target of FSM is the forest sector, which is usually understood as comprising an upstream segment, forestry, and a downstream segment, forest industries (Solberg 1986). Forestry encompasses forest resources, their biological dynamics (e.g., growth, mortality) and timber harvesting, while forest industries encompass the processing and transportation of wood products and their sale onto the market. The exact boundaries of the forest sector are not clearly defined, and models do not share the same exact targets. On the forestry side, the least detailed models do not describe the resource, or only as aggregated timber volumes, while more detailed models distinguish between several tree species, diameter classes, ownership categories and are spatially-explicit (Lobianco, Delacote, et al. 2016; Sjølie, Latta, Gobakken, et al. 2011). On the industry side, several market levels can be represented (Johnston and van Kooten 2014). Most models include several products (e.g., roundwood and pulpwood), and many include a second level in transformed products (e.g., plywood, lumber.). Generalist models focus on traditional wood products used for construction, furniture and paper, while specialized models focus on specific industries such as wood chips (Kallio et al. 2011) or biofuels (Mustapha, Trømborg, and Bolkesjø 2017). FSM vary in their geographical scopes and spatial formats, and can be developed at the country (Adams, Mccarl, and Murray 2005;

Caurla, Delacote, Lecocq, Barthès, et al. 2013; Hänninen and Kallio 2007), regional (Kallio, Moiseyev, and Solberg 2004; Chudy et al. 2013) or global levels (Buongiorno 2014; Favero, Mendelsohn, and Sohngen 2018). Most models are spatialized and include several demand and supply regions, but a few are aspatial with a single region (Schwarzbauer and Rametsteiner 2001).

FSM are equilibrium models where market equilibrium is found by equating supply (quantity of timber produced) and demand (quantity consumed) for all products. The majority of models finds the so-called spatial price equilibrium (Samuelson 1952) by solving a large mathematical programming problem where the sum of consumer and producer surpluses net of transport costs, or net social surplus (NSS), is maximised under a set of constraints ensuring non-negativity of key variables and enforcing lower and upper bounds for some of them (Buongiorno 2014; Latta, Sjolie, and Solberg 2013). In a case with several products *k* and regions (*i,j*), NSS is equal for a given year *t* to:

$$[1] \quad NSS_t(D_{ikt}, S_{ikt}, e_{ijkt}) = \sum_{ik} \int_0^{D_{ikt}} P_{ikt}(D_{ikt}) dD_{ikt} - \sum_{ik} \int_0^{S_{ikt}} P_{ikt}(S_{ikt}) dS_{ikt} + \sum_{ijk} TC(e_{ijkt})$$

where *D* refers to quantities demanded, *S* to quantities produced, *e* to quantities transported between regions and *TC* to transport costs (adapted from Kallio et al.(2008) and Buongiorno (2014)). The term $\int_0^{D_{ik}} P_{ik}(D_{ik}) dD_{ik}$ corresponds to areas under demand curves (consumer surplus), the term $\int_0^{S_{ik}} P_{ik}(S_{ik}) dS_{ik}$ to areas under supply curves (producer surplus), and the term $TC_{ijk} e_{ijk}$ to transport costs.

FSM are usually separated into two categories based on their handling of time (Sjølie et al., 2011). Intertemporal models assume agents have perfect foresight and solve all market equilibria at the same time. These models are well suited for long-term analyses (Latta, Sjolie, and Solberg 2013). On the opposite, recursive models assume limited foresight and solve equilibria one period at a time. They are made dynamic by recursively updating the model's parameters (Buongiorno 2014), and are better suited for short to medium-term analyses. In addition, some models are purely static (Johnston and van Kooten 2016). In the case of a recursive model, the optimisation for a given year *t* can be written as:

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

with rules on how parameters should be updated after each time period. For example, supply equations in the French Forest Sector Model (FFSM, Caurla et al. 2010) are given by:

$$[3] \quad S_{ikt} = S_{ikt-1} * \left(\frac{P_{ikt}}{P_{ikt-1}}\right)^{\alpha_k} * \left(\frac{F_{ikt}}{F_{ikt-1}}\right)^{\beta_k}$$

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 year. Similarly, I_{ikt} is the available forest inventory (timber volume) in year *t* and $I_{ikt-1}$the available inventory the previous year. α_k and β_k are the elasticities of supply to inventory and prices respectively. When the model is intertemporal, all equilibria are solved at the same time and the sum of discounted surpluses is maximised over the time horizon T using discount rate r:

$$[4] \quad \forall t \in [0, T], \; Max_{D_{ikt}, S_{ikt}, e_{ijkt}} \left(\sum_{t=0}^{T} (1+r)^{-t} NSS_t(D_{ikt}, S_{ikt}, e_{ijkt}) \right)$$

The determination of quantities produced, consumed, traded and prices is endogenous. Elasticities are usually estimated econometrically or taken from the literature, and trade data (e.g., from the FAO) and forest inventory data (e.g., from national forest inventories) are used to calibrate the models. A small number of models do not follow the general framework described here. For example, the model developed by Schwarzbauer & Rametsteiner (2001) falls within the Systems Dynamics framework, where demand and supply are not determined simultaneously in an optimisation process, but oscillate around equilibrium values. For more details regarding FSM, the reader can refer, among others, to Buongiorno (1996, 2014), Latta, Sjolie and Solberg (2013) or Northway, Bull and Nelson (2013).

2.2. Non-timber objectives

Forest management can be defined as "the integration of silvicultural practices and business concepts in such a way as to best achieve a landowner's objectives" (Bettinger et al. 2017). The main objective pursued by landowners is usually timber production. This is illustrated by early works on optimal forestry practices such as that of Faustmann (1849), where maximising returns from wood production is the key element. However, forest management can pursue several objectives in addition to the production of wood (Carvalho-Ribeiro, Lovett, and O'Riordan 2010), and terms such as "multiple-use" or "multifunctional" are often encountered (Carvalho-Ribeiro, Lovett, and O'Riordan 2010; Hall 1963; Mander, Wiggering, and Helming 2007). This multiplicity of potential objectives is recognised in the definition of "sustainable forest management" (MCPEF 1993), and the FAO FRA database (FAO 2012, 2018) uses a classification of forestland according to their management objectives, illustrating the diversity of objectives that can be pursued (Table 2.1).

Many objectives relate to the provision of ecosystem services, which can be broadly defined as "the direct and indirect contributions of ecosystems to human wellbeing" (TEEB 2010) and are often categorized as "provisioning services", "regulation services" or "cultural services" (Haines-Young and Potschin 2018). To give an example, we included in Table 2.1 forest ecosystem services reviewed by Krieger (2001) in their assessment of forest ecosystem values, but some classifications name up to 100 services (Aznar-Sánchez, Belmonte-Ureña, López-Serrano, and Velasco-Muñoz 2018). Not all objectives fall under the scope of ecosystem services. Biodiversity conservation is often cited as a management objective, but biodiversity is usually considered not to be a service, rather a support for services, or even a good (Mace, Norris, and Fitter 2012). Other objectives are revealed when looking at individual owners' motivations for owning forests (Côté et al. 2017; Hugosson and Ingemarson 2004; Kumer and Štrumbelj 2017; Kuuluvainen, Karppinen, and Ovaskainen 1996; Põllumäe, Korjus, and Paluots 2014), and a short review reveals that some would be located further down the ecosystem services cascade and could be considered benefits (e.g., financial stability, passing on to the next generation). Because of the diversity in classifications and definitions, we chose to use the general term "non-timber objective" to refer to all finalities pursued by forest owners through forest management other than the production of timber.

Table 2.1 - Examples of forest management objectives and forest ecosystem services (FAO 2018; Krieger 2001).

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

2.3. Review methodology

We follow a two-step process, as illustrated in Figure 2.1. In the first step, we systematically gather scientific publications using Scopus database. A first search query aims at retrieving publications based on historically significant FSM, using the models' names and abbreviations for them. The list of FSM included in the query is based on publications on the development and history of FSM (Adams and Haynes, 2007; Toppinen and Kuuluvainen, 2010; Latta, Sjolie and Solberg, 2013; Northway, Bull and Nelson, 2013). A second search query uses keywords related to common denominations used to describe FSM, alongside keywords related to the forest sector and economics. This allows us to retrieve publications where other FSM are used. In order to sort articles obtained from the query, and in line with the literature (Solberg, 1986; Adams and Haynes, 2007; Latta, Sjolie and Solberg, 2013; Northway, Bull and Nelson, 2013; Wear and Coulston, 2019), we narrow the definition of FSM to models (1) rooted in economic theory, (2) representing the forest sector, i.e., forestry plus forest industries, (3) at the sectoral scale, and (4) at a temporal scale relevant to forest-related questions (when models are dynamic). 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 exclude models at the individual owner or forest stand scale, and biological growth models.

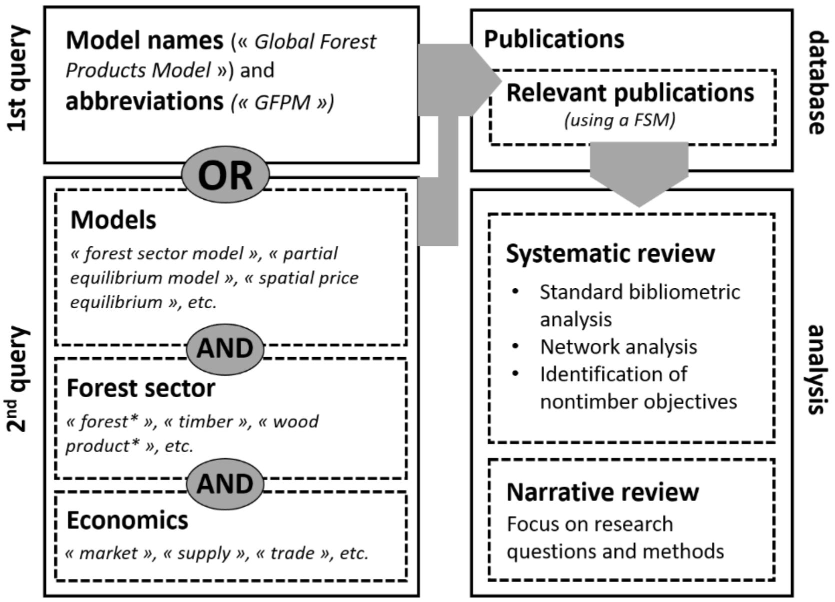

Figure 2.1 - Illustration of the review process: search queries used (left) and analysis of retrieved papers (right).

In a second step, we analyse publications in the review dataset. We perform standard bibliometric analyses and we carry out a bibliometric network analysis based on keyword co-occurrence using VOSviewer[17] (van Eck and Waltman 2010; Eck and Waltman 2018). Based on titles, abstracts and keywords (and, when necessary, full-texts), we identify papers dealing with non-timber objectives and identify which objectives are being investigated. In addition to this quantitative review, we perform a more in-depth narrative review. We give an overview of research questions (i.e., which aspects of non-timber objectives are being investigated?), review modelling approaches to the inclusion of non-timber objectives and identify current modelling trends.

3. Systematic review and bibliometric analyses

3.1. Paper count and publishing dynamics

The systematic review yields 248 publications. As shown on Figure 2.2, the amount of paper published annually has been increasing steadily, and since 2005 at least 9 papers have been published every year. As we conducted the review in July 2019, paper count for 2019 may still increase. We separated papers into two categories: analyses, where a model is used to answer a research question about the forest sector, and non-analyses, which comprise reviews, theoretical contributions and model presentations. We found 51 non-analyses and 197 analyses. Among analyses, 56 (28%) did not consider a non-timber objective, and 141 (72%) did. While the amount of papers considering timber production alone has stayed relatively

[17] 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.

constant over time, the amount of papers focused on non-timber objectives has strongly increased in recent years. Since 2010, half or more of papers published every year have included non-timber objectives.

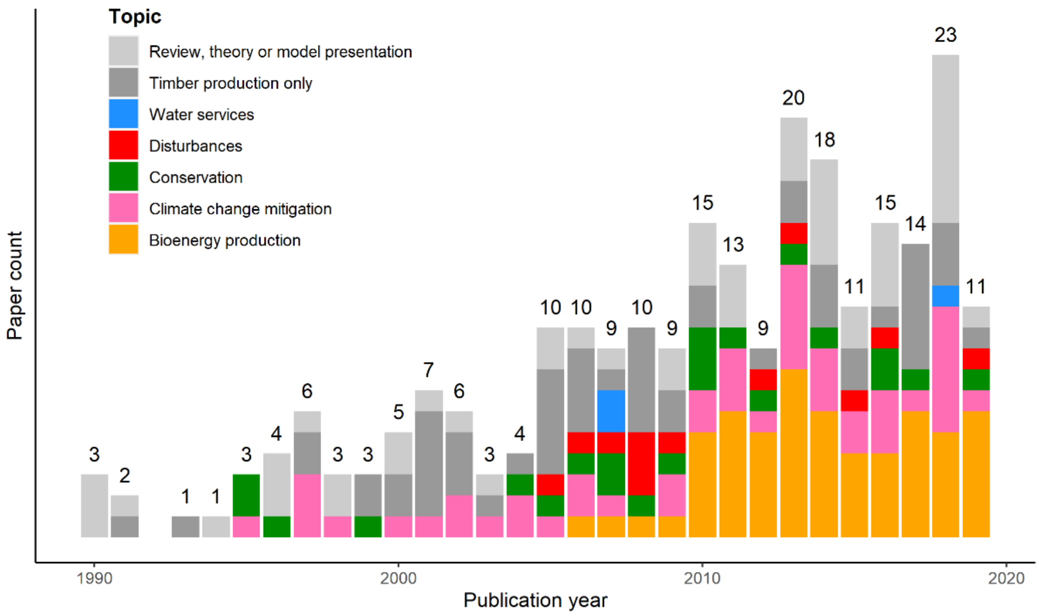

Figure 2.2 – Distribution of reviewed papers per date of publication and thematic focus.

As shown in Table 2.2, a few journals concentrate most papers. The most common are specialised forest economics journals (e.g., *Forest Policy and Economics*, *Journal of Forest Economics*) and generic forest sciences journals (e.g., *Forest Science*, *Scandinavian Journal of Forest Research*). Of lesser importance but still well represented are journals specialised in energy and climate issues (e.g., *Energy Policy, Biomass and Bioenergy, Climatic Change*) and resource economics journals (e.g., *Agricultural and Resource Economics Review*, *Environmental and Resource Economics*). Few papers are published in general economics journal (e.g., 1 and 2 papers in the *American Economics Review* and *Applied Economics* respectively) or modelling journals (e.g., *Ecological Modelling* and *Environmental Modelling and Assessments* both have two papers). The Scopus subject areas[18] most represented are Agricultural and Biological Sciences (175 papers), Environmental Sciences (166), Social Sciences (74), Economics, Econometrics and Finance (67) and Energy (34).

We propose two possible explanations for these trends: First, researchers in the field may focus their publications on journals specialised in forestry (with a focus in economics or not) rather than journals that are more generic. This may be linked to the fact that, historically, forest sector modelling developed within an already specialised field, that of forest economics (Buongiorno 1996). Second, journals that are more generic may have a lower degree of openness to applied, forest-related topics. Both explanations are a concern, given the wide environmental importance (climate change, biodiversity) that forests have for society.

[18] 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.

In addition, we note the relative absence of modelling journals, which could indicate a focus in published papers on results and policy implications rather than on methods and modelling tools. In the papers we reviewed, those published in modelling journals were focusing on the development of new "modules" within already established models (Lobianco et al. 2015; Lobianco, Delacote, et al. 2016; Petucco, Lobianco, and Caurla 2019) or developed new models (Härkönen et al. 2019) and contained detailed information about model specifications. However, the vast majority of papers reviewed contained much less information: given the large size and complexity of FSM, details about modelling techniques are usually published as separate books or technical reports (Buongiorno et al. 2003; Kallio, Moiseyev, and Solberg 2004).

Table 2.2 - 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
Total	**129 (52%)**		**295**[19]

Most of the research activity seems to take place in developed countries with large forest industries (and hence policy relevance), especially those where the research field originated and where research programmes are likely well established. As shown in Table 2.2, the country most represented in authors' institutional affiliations is by far the United States, which is where a large part of FSM research started (Latta, Sjolie, and Solberg 2013). Besides, several models with regional, national and global scopes still in use today are being developed by US-based institutions (Abt, Cubbage, and Pacheco 2000; Adams, McCarl, and Murray 2005; Buongiorno et al. 2003). European countries such as Sweden, France, Finland, Norway, Germany and Austria are also well represented. These all share the characteristic to have extensive forest areas and/or a large forest industry. Besides, one of the early clusters of model development was based at IIASA, an international research organisation located in Austria (Latta, Sjolie, and Solberg 2013). New-Zealand and Canada, which also possess significant forest sectors, are also well represented. Countries from other continents are almost absent, in particular countries with tropical forests, despite their environmental and economic

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

relevance. Instead, most issues related to tropical forests (illegal logging mostly) appear in our review to be studied using global models developed in the USA or in Europe, with a focus on international trade (Li et al. 2008; Moiseyev et al. 2010; Mosnier et al. 2014), even when no authors are affiliated to these countries (Zhang et al. 2016). This point may be explained by the fact that most research related to tropical forests focuses on land-use change and deforestation, issues that go beyond the scope of the forest sector alone. This implies that tropical forests are more likely to be treated trough land-use change models rather than FSM.

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

We report results from the bibliometric network analysis as a network of keywords in Figure 2.3. Two clusters (A and D) comprise keywords associated with the production of timber and wood products. Cluster A has a stronger focus on forest industries and timber markets, illustrated by keywords such as "trade", "competition", "timber market" or "demand/supply", while cluster D has a stronger focus on forestry, with keywords such as "forest", "forest management" and "timber". Cluster B is associated with the production of renewable energy from woody biomass ("bioenergy", "biomass", "renewable energy/resource", "fossil fuel"), and cluster C is associated with forest carbon and climate change ("climate change", "carbon", "carbon sequestration", "land use change", "greenhouse gas"). Together, clusters B and C refer to the forest sector's contribution to climate change mitigation through energy substitution and carbon sequestration. Keywords referring to methods used, such as "forest sector model", "partial equilibrium model" or "computer simulation" are distributed among all clusters.

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

- We chose to consider bioenergy products separately from traditional wood products for three reasons. First, their inclusion in the FSM literature is recent and represents a significant amount of publications where the focus is on technology-intensive products. Second, in forest sciences, fuelwood production is often considered separately from regular timber or paper production. Third, papers often adopt a climate perspective based on energy substitution and avoided emissions, and we consider climate change mitigation to be a non-timber objective. However, we separate "bioenergy" papers from "climate change" papers because of their specialized and deep focus. The latter have a broader scope, while the former are in-depth analyses of bioenergy industries and their development potential.
- Disturbances such as fires or storms affect the forest's ability to provide goods and services. In order to mitigate risks associated to these disturbances, managers may take actions they would otherwise no take (e.g., prescribed burning). Besides, disturbances affect both timber and non-timber objectives (e.g., habitats for biodiversity, carbon stored) and, in some cases, only affect non-timber objectives. For example, lowland Mediterranean forests produce little timber, but are heavily managed both at the stand and landscape levels to mitigate fire risks due to threats posed to biodiversity, recreational uses or human settlements (Fernandes et al. 2013). In such a case, fire prevention can even

become the main objective. Hence, we chose to consider the regulation of risks associated to disturbances as a separate non-timber objective.

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

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

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

We illustrate this with a commonly introduced non-timber objective, *in-situ* carbon sequestration, i.e., in forests. The first step of any inclusion of carbon sequestration into FSM is the quantification of carbon stocks and fluxes. To achieve this goal, many modellers have opted for the development of "carbon accounting modules", i.e., registries where amounts of carbon stored in several compartments are tracked over time (Adams, McCarl, and Murray 2005; Lobianco, Caurla, et al. 2016; Trømborg and Sjølie 2011). Because carbon quantities are directly linked to forest biomass, these accounting modules rely on forest inventory submodels already present in most FSM and use expansion factors to convert cubic meters of wood to tons of carbon. Wear and Coulston (2019) provide a detailed overview of the main assumptions behind forest inventory modules used to project carbon dynamics in FSM. Alternatively, the description of forest resources within some FSM may be too aggregated to allow for a good conversion to carbon contents. In this case, specialised ecological models can be mobilised, as in Kallio *et al.* (2013), where FSM outputs are used as inputs to a forest stand growth simulator where the development of forest biomass and carbon stocks is simulated with more accuracy.

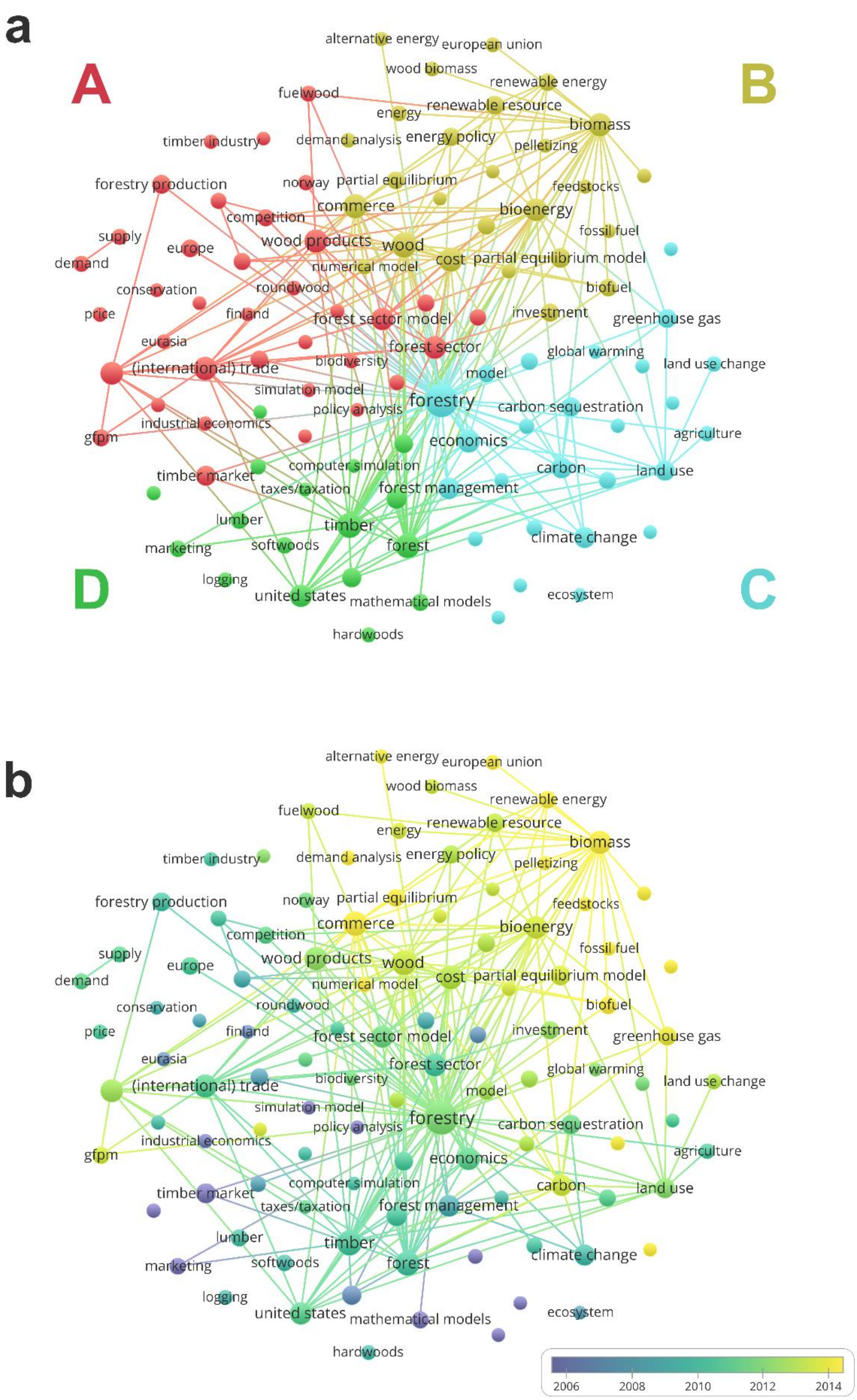

Figure 2.3 - Bibliometric network analysis based on keyword co-occurrence (a), and temporal trends in keyword use (b). The size of items is proportional to the number of occurrences, and distances between items indicate their level of relatedness. For visibility purposes, we limited the display to the most common 105 keywords, which corresponds to at least 8 occurrences within the dataset, and only the 500 strongest links are displayed. In figure (a), keywords clusters are represented in different colours, while figure (b) displays the average year keywords were used in.

Then, the inclusion of carbon sequestration into FSM can take two routes. Firstly, it can be introduced as an objective through monetisation and subsequent addition to the objective function. A price is given in monetary units per ton of carbon, many estimates being available in the literature (Rogelj et al. 2018). Landowners receive a yearly payment equal in year t to $P_{c,t}(\Delta C_t - \Delta C_t^{BAU})$, where $P_{c,t}$ is the price of carbon in year t, ΔC_t the change in carbon stock between years t and t-1, and ΔC_t^{BAU} the stock change in a baseline scenario[20]. Hence, the sum $\sum_{t=0}^{T}(1+r)^{-t}P_{c,t}(\Delta C_t - \Delta C_t^{BAU})$ of payments received by landowners over a period T can be directly added to NSS in the objective function in equation (4) (e.g., Im, Adams and Latta, 2007; Latta et al., 2011a; Sjolie, Latta and Solberg, 2013). In the case of recursive models, the supply function is modified to account for the opportunity cost to harvesting due to carbon payments which acts as a tax, e.g. equation (3) becomes:

$$[5] \quad S_{ikt} = S_{ikt-1} * \left(\frac{P_{ikt} - \omega_{kt} * P_{c,t}}{P_{ikt-1} - \omega_{kt} * P_{c,t-1}}\right)^{\alpha_k} * \left(\frac{F_{ikt}}{F_{ikt-1}}\right)^{\beta_k}$$

where ω_k is the carbon density of product k, and $\omega_k P_{c,t}$ represents the foregone carbon payment due to timber being extracted from the forest. Carbon payments themselves need to be added to producer surplus ex-post (Buongiorno and Zhu 2013; Lecocq et al. 2011). In most applications, carbon sequestration is assumed to be an objective pursued on all forestland. However, in Latta *et al.* (2011), the model endogenously determines land where this objective is to be pursued, and the amount of land enrolled in the carbon sequestration programme is introduced as a decision variable.

Secondly, when carbon sequestration objectives are not included in the objective function, they can be introduced as constraints to the maximisation of net social surplus. In Im *et al.* (2010), this takes the form of a constraint on carbon fluxes within the forest sector:

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

where ΔC_t^f and ΔC_t^p are changes in carbon stocks in the forest and products pools respectively, discounted by discount rate r, and T_{min}^C is the carbon flux target over period T. Alternatively, due to the direct relationship between timber volume and carbon quantities, the constraint can be set as an upper limit to timber harvests (Im, Adams, and Latta 2010; Kallio and Solberg 2018; Kallio et al. 2018). In the next section, these various approaches are reviewed for each category of non-timber objective.

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

4.1. Research questions and transversal issues

FSM were originally developed as market models to perform economic analysis. As illustrated by the high number of papers focusing on non-timber objectives, they have gradually become

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

tools for environmental assessment as well. However, many non-timber objectives are only studied insofar as they affect economic activity and timber production, while others such as bioenergy production are more deeply integrated. We illustrate this fact by giving an overview of research questions and modelling approaches for each non-timber category.

Bioenergy papers largely aim at assessing the potential to develop bioenergy industries, their ability to reach renewable energy targets and implications for traditional timber industries (Bolkesjø, Trømborg, and Solberg 2006; Li et al. 2008; Moiseyev et al. 2011; White et al. 2013). A strong focus is put on assessing the effectiveness of economic policy measures such as subsidies to bioenergy production or consumption (Caurla, Delacote, Lecocq, and Barkaoui 2013; Kangas et al. 2011; Sjølie et al. 2010). Even though the early focus was on bioenergy markets themselves, recent contributions to the topic are increasingly concerned with the environmental footprint of bioenergy products, and deal with issues such as carbon neutrality (Earles et al. 2012; Sjølie et al. 2010), carbon stocks and land-use patterns (Böttcher et al. 2013; Havlík et al. 2011; Okoro, Schickhoff, and Schneider 2018) and implications for landscapes and habitats (Costanza et al. 2017; Duden et al. 2017; Geijer et al. 2014). Conversely, several contributions in the conservation category investigate the impacts of bioenergy policy (Geijer, Bostedt, and Brännlund 2011; Schleupner and Schneider 2010). The integration of bioenergy is the one we believe to be the deepest, owing to the fact that bioenergy production is easily quantifiable in both physical and monetary units the same way as regular timber products, i.e., with a market model assigning prices to quantities produced. In addition, bioenergy products (e.g., pellets) are already traded on markets, and data is accessible to calibrate models. Hence, bioenergy production is often introduced as an endogenous objective in models, and quantities produced are decision variables. In some cases, energy demand is constrained to account for exogenous renewable energy production targets.

Papers on climate change mitigation focus on two broad research questions. First, 13 papers seek to inform general forest policy by evaluating the impacts of climate change on timber markets, industries and forest resources (Beach et al. 2015; Perez-Garcia, Joyce, and McGuire 2002; Solberg, Moiseyev, and Kallio 2003). Second, 32 papers investigate the climate mitigation potential of the forest sector and seek to evaluate the costs and effectiveness of mitigation policies and strategies. Most of these papers include quantification of carbon fluxes, and rely on the use of the aforementioned carbon accounting modules, conversion factors or external models to do so. Carbon pricing is a straightforward and established economic method to assign monetary values to carbon stored and avoided emissions (van Kooten and Johnston 2016), allowing for a good integration to FSM. Indeed, 20 papers rely on carbon pricing, either payments for sequestration in forests (Adams et al. 2011; Buongiorno and Zhu 2013; Lecocq et al. 2011), or sector-wide carbon tax-subsidy schemes (Moiseyev, Solberg, and Kallio 2014; Sjølie, Latta, and Solberg 2014). Carbon prices are usually set by the user, with some exceptions where carbon prices are endogenously determined (Favero and Mendelsohn 2014; Tavoni, Sohngen, and Bosetti 2007). Other approaches include setting constraints to the optimization in terms of harvest levels (Kallio and Solberg, 2018; Kallio et al., 2018), and more rarely, carbon fluxes (Im, Adams, and Latta 2010), eschewing monetization. Some models include the area committed to sequestration as a decision variable (Latta et al. 2011).

Other non-timber objectives are less deeply integrated. Most conservation papers seek to assess tradeoffs between economic activity and habitat conservation, usually quantified in loss of economic surplus or reduced timber supply (Bolkesjø, Trømborg, and Solberg 2005;

Geijer, Bostedt, and Brännlund 2011; Hänninen and Kallio 2007; Kallio, Moiseyev, and Solberg 2006; Schleupner and Schneider 2010). Several papers focus on tradeoffs in deforestation-prone areas (Barbier et al. 1995; Merry et al. 2009; Mosnier et al. 2014) and three papers assess the economic implications of barriers to the trade of illegal timber (Moiseyev et al. 2010; L. Sun and Bogdanski 2017; Zhang et al. 2016). In most cases, conservation does not enter the objective function, is not modelled explicitly and is introduced through constraints to the optimization problem, i.e., land is removed from production, harvest levels or traded quantities are constrained as proxies for conservation practices. Noteworthy exceptions in the sample include Kallio et al. (2008) and Schleupner and Schneider (2013), where the location of land to be conserved is a decision variable. Similarly, two papers on water services follow a constraint-based approach where forests around streams cannot be harvested (Adams and Latta, 2005, 2007).

The topic of disturbances revolves around three issues: pests and diseases (7 papers), forest fires (3), and storms (2); they are approached through the economic cost and sectoral impacts of prevention measures or *ex-post* recovery plans (Adams and Latta 2005; Caurla, Garcia, and Niedzwiedz 2015; Ince et al. 2008; Prestemon et al. 2013; Prestemon, Abt, and Huggett 2008; Sun 2016; Turner et al. 2007). Only a few papers quantified the impacts of forest policy on habitat quality (Geijer et al. 2014; Pattanayak et al. 2004), and one paper quantifies water quality and quantity implications of climate mitigation policies (Yu et al. 2018). They rely on specialized exogenous models, e.g. habitat suitability or hydrology models.

Overall, examples of non-timber objectives included in the objective function encompass carbon sequestration, through carbon pricing, and bioenergy production, through market prices and econometrically estimated supply and demand functions. Examples are rarer for other objectives, which are most often only quantified in biophysical units, and either do not enter decision rules or as constraints to the optimisation problem. Some non-timber objectives are notably lacking from our sample. Forest recreation and more generally cultural services are absent, while it is an important topic in the ecosystem services literature (Hernández-Morcillo, Plieninger, and Bieling 2013). Management for the provision of regulation services is limited to those that directly affect the economic profitability of forest activities, such as pests, fires and storms, and only three papers deal with water services.

Natural processes within forestry, especially those related to disturbances, are characterised by a high level of uncertainty (Hanewinkel, Hummel, and Albrecht 2011). Other uncertainties concern the evolution of prices, trade patterns, as well as parameters estimated for the models (Kallio 2010). FSM are deterministic models, and uncertainties are traditionally treated by performing sensibility analyses (Chudy, Sjølie, and Solberg 2016). However, we witnessed that the introduction of uncertainty constitutes a recent, albeit minor focus in FSM research. Three papers use probabilistic approaches such as Monte-Carlo simulation to account for uncertainty (Buongiorno and Johnston 2018; Jåstad et al. 2018; Kallio 2010), and one paper is a review dedicated to uncertainty (Chudy, Sjølie, and Solberg 2016). Other recent contributions focus on re-estimating parameters and assessing the reliability of international databases used for model calibration (Kallio and Solberg, 2018; Morland et al., 2018; Rougieux and Damette, 2018).

4.2. Modelling trends and implications

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

First, owing to the strong focus on bioenergy and climate issues, many FSM have become specialised models. From 2005 onwards, we witness a multiplication of models where segments of the energy sector are added, and some models have been developed for specific bioenergy markets (Kallio et al. 2011; Mustapha, Trømborg, and Bolkesjø 2017). This implies an increase in model complexity: models must be able to accurately represent biomass feedstocks, processing technologies and energy demand, and require data for model calibration that is both reliable and readily available. For example, the model in Tromborg *et al.* (2007) includes 12 bio-heating technologies and 3 types of biomass from 6 different feedstocks in addition to conventional wood products and industries. Many models have been enhanced to include the above-mentioned carbon accounting modules (Wear and Coulston 2019): these rely on assumptions regarding the carbon content of biomass and harvested wood products, their decay over time, and require information on GHG emissions from various processes as well as substitution coefficients to estimate avoided emissions. Such analyses entail the use of life-cycle-analysis or other methods to assess parameters, on which uncertainties remain (Earles et al. 2012; Sjølie and Solberg 2011). A parallel trend is well-documented for Integrated Assessment Models (IAM) of the energy-climate system which are commonly used to evaluate climate policy. In recent years, many so-called hybrid IAM have been developed, which embed a detailed description of energy-producing technologies within a general top-down aggregated framework (Bosetti et al. 2005; Cai et al. 2015). Such models face challenges in terms of computational requirements and complexity, theoretical consistency and empirical validity, as well as policy relevance (Hourcade et al. 2011). This last point is of particular importance. Many FSM have become close to biomass-for-bioenergy supply chain models which are increasingly used to investigate the development potential of bioenergy industries and design supply chains at local scales and on generally shorter time horizons (De Meyer et al. 2014; Shabani, Akhtari, and Sowlati 2013). While methods and the study object are similar, modellers should keep in mind that despite potential similarities, different models are built to answer different questions. The focus in FSM research should stay on assessing energy policy in the forest sector from a broad, social planner perspective, in particular concerning the articulation with other objectives, traditional timber industries and the availability of forest resources. While this does not exclude technical refinements necessary to an accurate representation of bioenergy production, it entails finding a balance between model complexity and system completeness.

Second, the assessment of many non-timber objectives requires detailed, spatially explicit data on environmental conditions. Many FSM were originally developed at the global and national scales, and use aggregated data. We witnessed in our sample a recent trend towards the development of new models with restricted geographical scopes, or the downscaling of already existing models to lower spatial scales. For example, a spatially explicit version of the FFSM was developed from the national model in order to account for variability in environmental conditions (Lobianco et al. 2015), and a subnational module was developed for the USA for the Global Forest Products Model (Ince et al. 2011). Several new models were created for individual Canadian provinces (Niquidet and Friesen 2014; Peter and Niquidet 2016), as well as for the Scandinavian region (Mustapha, Trømborg, and Bolkesjø 2017).

Several papers we reviewed use Geographical Information System software (Galik and Abt 2016; Schleupner and Schneider 2013), and the newly developed LURA model uses plot-level forest data and individual plant-level data to produce a very spatially disaggregated model (Latta, Baker and Ohrel, 2018). While earlier studies had to rely on ad-hoc criteria and proxies to model objectives such as conservation, this new generation of FSM is better equipped to handle non-timber objectives. Consequently, we expect the modelling of non-timber objectives to improve as these models develop, and we expect an increasing amount of studies focusing on non-timber objectives, including those still missing today. However, global and national models remain well-equipped to handle issues such as leakages or international trade distortions, and for this reason should not be abandoned (Buongiorno and Zhu, 2013; Kallio and Solberg, 2018).

Third, many modellers have turned to the use of other, specialised models, coupling them to FSM in order to compensate for their weaknesses and expand the range of analyses possible. The most common type of coupling is established with models in environmental sciences. These include general circulation models to account for climate change (Favero, Mendelsohn, and Sohngen 2018; Perez-Garcia et al. 1997), landscape succession (Costanza et al. 2017) or habitat quality models (Kallio et al. 2008; Pattanayak et al. 2004) to account for environmental impacts, or forest growth simulators and soil models to calculate carbon fluxes (Eriksson et al. 2012; Im, Adams, and Latta 2010). Another common linkage established is with energy models (Caurla et al. 2018) or IAM (Tavoni, Sohngen, and Bosetti 2007), which is an alternative to the specialisation of FSM described earlier. Our sample also included the use of model couplings to study regulation services, for example with spread models for pathogens (Petucco, Lobianco, and Caurla 2019) or hydrology models (Yu et al. 2018). This trend to develop "Economic Environment Integrated Models" is documented in the wider environmental modelling field, and is a welcome development since it enables performing new analyses (Beaussier et al. 2019). However, it also increases complexity for modellers, who are required to ensure compatibility between models in terms of data requirement and their main assumptions. Besides, most couplings are established between a market model (FSM) and models in environmental sciences. While results are more comprehensive with regards to the multiple facets of forestry, interdisciplinary research is not without challenges, which can be both structural and conceptual in nature and should be taken into account when designing research projects (Campbell 2005; Sievanen, Campbell, and Leslie 2012).

4.3. Current frontiers and avenues for future research

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

Investigating such non-timber objectives often requires modelling the forest sector and forest resources at the local or sub-regional levels. Biophysical and economic assessment studies for many regulation and cultural services often rely on fine scale, spatially explicit data, such as the presence of recreation equipment, landscape viewpoints, topographic data at the local scale, etc. (Tardieu and Tuffery 2019). Even though many FSM are spatialized, they are so at more aggregated levels (e.g. regions) and are ill equipped to handle such information. Modelling such objectives also entails the inclusion of specific management practices (e.g., continuous-cover, close to nature forestry, etc.) as well as releasing the representative economic agent assumption to better represent heterogeneity in behaviours and preferences regarding environmental objectives. FSM were not originally developed to face such challenges, and even when technical refinements are made, data is often lacking to calibrate models such as Lobianco et al. (2015, 2016) and Latta, Baker and Ohrel (2018). Besides, the objective function of most FSM is an economic surplus, which requires non-timber objectives to be monetized and consequently hampers the inclusion of those for which monetary values are hard to estimate. Assessing the economic value of regulation services not linked to markets, and of most cultural services, remains elusive (Chan, Satterfield, and Goldstein 2012). As a consequence, objectives in FSM are often modelled at two levels: some as constraints, others as decision variables within the optimization problem, which implies the precedence of some objectives on others. In some cases, objectives are not quantified, and significant simplifications are made to model objectives located further away from FSM's original targets (e.g., limits on harvests as a proxy for habitat conservation).

To improve the integration of non-timber objectives in FSM, future research should focus on building reliable databases of local environmental and economic conditions from which models can be calibrated. Research may also benefit from additional information regarding forest owners' attitudes towards non-timber objectives and their inclusion within traditional forest management practices. Such information could be obtained through surveys, focus groups or laboratory experiments, which also presents the advantage of anchoring research within a stakeholder-oriented dynamic. Once such information is available, an interesting direction to explore is that of Agent-Based Models (ABM). ABM are bottom-up models where dynamics at the system level arise from the combination of and interactions between multiple, individual agent-level decisions. Like traditional FSM, ABM can be based on both economic theory and empirical data, but may be better suited to the investigation of complex social-ecological systems with a high degree of heterogeneity (An 2012; Heckbert, Baynes, and Reeson 2010; Janssen and Ostrom 2006). Following the first steps made by Lobianco *et al.* (2016) and Pohjola *et al.* (2018), we believe such a direction could improve the modelling of environmental and behavioural diversity in FSM.

Regarding models themselves, the representation of forest resources is of particular importance. While many FSM are able to quantify the resource using multiple strata (e.g., diameter classes, ownership categories, etc.), little attention has been paid to the spatial organization of this resource. Moving from a volume-based description of forest inventories to a landscape-based approach could improve the models' ability to investigate non-timber objectives, in particular those related to regulation and cultural ecosystem services as well as biodiversity. Future efforts could also focus on reformulating the objective function as a multi-objective function where all objectives are integrated in a similar way, and where biophysical units can be used. For example, Yousefpour *et al.* (2018) follow a goal programming approach and use a multi-objective function composed of the Net Present Value for commercial timber production and of carbon sequestration fluxes, to which different weights are attributed. Such multi-objective methods are commonly used in applied forest management (Mendoza and Martins 2006), and could be developed within and benefit the FSM research field and allow for the inclusion of objectives for which the evaluation of economic value in monetary units is the main limitation.

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

5. Conclusions

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

References

Abt, Robert C, Frederick W Cubbage, and Pacheco. 2000. "SOUTHERN FOREST RESOURCE ASSESSMENT USING THE SUBREGIONAL TIMBER SUPPLY (SRTS) MODEL." *Forest Products Journal* 50(4): 25–25.

Adams, D.M., and G.S. Latta. 2007. "Timber Trends on Private Lands in Western Oregon and Washington: A New Look." *Western Journal of Applied Forestry* 22: 8–14.

Adams, Darius M, Ralph Alig, Greg Latta, and Eric M White. 2011. "Regional Impacts of a Program for Private Forest Carbon Offset Sales." *Journal of Forestry* 109(8): 444–61.

———. 2007. "Future Prospects for Private Timber Harvest in Eastern Oregon." *WEST.J.APPL.FOR.* 22(3).

Adams, Darius Mainard, and Richard W. Haynes. 2007. *Resource and Market Projections for Forest Policy Development : Twenty-Five Years of Experience with the U.S. RPA Timber Assessment*. Springer.

Adams, Darius, Bruce A Mccarl, and Brian C Murray. 2005. *FASOMGHG Conceptual Structure, and Specification: Documentation*.

An, Li. 2012. "Modeling Human Decisions in Coupled Human and Natural Systems : Review of Agent-Based Models." *Ecological Modelling* 229: 25–36.

Aznar-Sánchez, José A Belmonte-Ureña, Luis J., María J. López-Serrano, and Juan F. Velasco-Muñoz. 2018. "Forest Ecosystem Services: An Analysis of Worldwide Research." *forests* 9: 1–19.

Barbier, Edward B., Nancy Bockstael, Joanne C. Burgess, and Ivar Strand. 1995. "The Linkages between the Timber Trade and Tropical Deforestation???Indonesia." *World Economy* 18(3): 411–42.

Beach, Robert H et al. 2015. "Climate Change Impacts on US Agriculture and Forestry: Benefits of Global Climate Stabilization." *Environmental Research Letters* 10(9).

Beaussier, Thomas, Sylvain Caurla, Véronique Bellon-Maurel, and Eleonore Loiseau. 2019. "Coupling Economic Models and Environmental Assessment Methods to Support Regional Policies: A Critical Review." *Journal of Cleaner Production* 216: 408–21.

Bettinger, Pete, Kevin Boston, Jacek P. Siry, and Donald L. Grebner. 2017. "Management of Forests and Other Natural Resources." *Forest Management and Planning*: 1–20.

Bolkesjø, Torjus Folsland, Erik Trømborg, and Birger Solberg. 2005. "Increasing Forest Conservation in Norway: Consequences for Timber and Forest Products Markets." *Environmental and Resource Economics* 31(1): 95–115.

Bolkesjø, Torjus, Erik Trømborg, and Birger Solberg. 2006. "Bioenergy from the Forest Sector: Economic Potential and Interactions with Timber and Forest Products Markets in Norway." *Scandinavian Journal of Forest Research* 21(2): 175–85.

Bosetti, Valentina et al. 2005. "Change Hybrud Model WITCH A World Induced Technical Change Hybrid Model Emanuele Massetti." *JSTOR*.

Böttcher, Hannes, Stefan Frank, Petr Havlík, and Berien Elbersen. 2013. "Future GHG Emissions More Efficiently Controlled by Land-Use Policies than by Bioenergy Sustainability Criteria." *Biofuels, Bioproducts and Biorefining* 7(2): 115–25.

Broadmeadow, S, and T R Nisbet. 2010. "The Effects of Riparian Forest Management on the Freshwater Environment: A Literature Review of Best Management Practice." *Hydrology and Earth System Sciences* 8(3): 286–305.

Brockerhoff, Eckehard G. et al. 2017. "Forest Biodiversity, Ecosystem Functioning and the Provision of Ecosystem Services." *Biodiversity and Conservation* 26(13): 3005–35.

Buchy, M, and S Hoverman. 2000. "Understanding Public Participation in Forest Planning: A Review." *Forest Policy and Economics* 1(1): 15–25.

Buongiorno, Joseph. 1996. "Forest Sector Modeling: A Synthesis of Econometrics, Mathematical Programming, and System Dynamics Methods." *International Journal of Forecasting* 12(3): 329–43.

———. 2003. "GFPM Structure and Formulation." In *The Global Forest Products Model*, Academic, 39–55.

———. 2014. "Global Modelling to Predict Timber Production and Prices: The GFPM Approach." *Forestry* 88(3): 291–303.

Buongiorno, Joseph, and Craig Johnston. 2018. "Effects of Parameter and Data Uncertainty on Long-Term Projections in a Model of the Global Forest Sector." *Forest Policy and Economics* 93(May): 10–17.

Buongiorno, Joseph, and Shushuai Zhu. 2013. "Consequences of Carbon Offset Payments for the Global Forest Sector." *Journal of Forest Economics* 19(4): 384–401.

Cai, Yiyong, David Newth, John Finnigan, and Don Gunasekera. 2015. "A Hybrid Energy-Economy Model for Global Integrated Assessment of Climate Change, Carbon Mitigation and Energy Transformation." *Applied Energy* 148: 381–95.

Campbell, Lisa M. 2005. "Overcoming Obstacles to Interdisciplinary Research." *Conservation Biology* 19(2): 574–77.

Carvalho-Ribeiro, S. M., A. Lovett, and T. O'Riordan. 2010. "Multifunctional Forest Management in Northern Portugal: Moving from Scenarios to Governance for Sustainable Development." *Land Use Policy* 27(4): 1111–22.

Caurla, Sylvain, Philippe Delacote, Franck Lecocq, Julien Barthès, et al. 2013. "Combining an Inter-Sectoral Carbon Tax with Sectoral Mitigation Policies: Impacts on the French Forest Sector." *Journal of Forest Economics* 19(4): 450–61.

Caurla, Sylvain, Vincent Bertrand, Philippe Delacote, and Elodie Le Cadre. 2018. "Heat or Power: How to Increase the Use of Energy Wood at the Lowest Cost?" *Energy Economics* 75: 85–103.

Caurla, Sylvain, Philippe Delacote, Franck Lecocq, and Ahmed Barkaoui. 2013. "Stimulating Fuelwood Consumption through Public Policies: An Assessment of Economic and Resource Impacts Based on the French Forest Sector Model." *Energy Policy* 63: 338–47.

Caurla, Sylvain, Serge Garcia, and Alexandra Niedzwiedz. 2015. "Store or Export? An Economic Evaluation of Financial Compensation to Forest Sector after Windstorm. The Case of Hurricane Klaus." *Forest Policy and Economics* 61: 30–38.

Caurla, Sylvain, Franck Lecocq, Philippe Delacote, and Ahmed Barkaoui. 2010. *The French Forest Sector Model: Version 1.0.*

Chan, Kai M.A., Terre Satterfield, and Joshua Goldstein. 2012. "Rethinking Ecosystem Services to Better Address and Navigate Cultural Values." *Ecological Economics* 74: 8–18.

Chudy, Rafal P., Hanne K. Sjølie, and Birger Solberg. 2016. "Incorporating Risk in Forest Sector Modeling – State of the Art

and Promising Paths for Future Research." *Scandinavian Journal of Forest Research* 31(7): 719–27.
Costanza, Jennifer K., Robert C. Abt, Alexa J. McKerrow, and Jaime A. Collazo. 2017. "Bioenergy Production and Forest Landscape Change in the Southeastern United States." *GCB Bioenergy* 9(5): 924–39.
Côté, Marc André, Ariane Généreux-Tremblay, Diane Gilbert, and Nancy Gélinas. 2017. "Comparing the Profiles, Objectives and Behaviours of New and Longstanding Non-Industrial Private Forest Owners in Quebec, Canada." *Forest Policy and Economics* 78: 116–21.
Van Delden, H., R Seppelt, R White, and A J Jakeman. 2011. "A Methodology for the Design and Development of Integrated Models for Policy Support." *Environmental Modelling and Software* 26(3): 266–79.
Diaz-Balteiro, Luis, and Carlos Romero. 2008. "Making Forestry Decisions with Multiple Criteria: A Review and an Assessment." *Forest Ecology and Management* 255(8–9): 3222–41.
Diaz, S. et al. 2019. *Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services-*
Duden, Anna S. et al. 2017. "Modeling the Impacts of Wood Pellet Demand on Forest Dynamics in Southeastern United States." *Biofuels, Bioproducts and Biorefining* 11(6): 1007–29.
Duncker, Philipp et al. 2012. "How Forest Management Affects Ecosystem Services, Including Timber Production and Economic Return: Synergies and Trade-Offs." *Ecology and Society* 17(4): art50.
Earles, J Mason, Anthony Halog, Peter Ince, and Kenneth Skog. 2012. "Integrated Economic Equilibrium and Life Cycle Assessment Modeling for Policy-Based Consequential LCA."
van Eck, Nees Jan, and Ludo Waltman. 2010. "Software Survey: VOSviewer, a Computer Program for Bibliometric Mapping." *Scientometrics* 84(2): 523–38.
Eck, Nees Jan Van, and Ludo Waltman. 2018. *VOSviewer Manual*.
Eriksson, Erik et al. 2007. "Integrated Carbon Analysis of Forest Management Practices and Wood Substitution." *Canadian Journal of Forest Research* 37(3): 671–81.
Eriksson, Ljusk Ola et al. 2012. "Climate Change Mitigation through Increased Wood Use in the European Construction Sector-towards an Integrated Modelling Framework." *European Journal of Forest Research* 131(1): 131–44.
FAO. 2012. 180 *FRA 2015 - Terms and Defintions*. www.fao.org/forestry/fra (June 13, 2019).
———. 2018. *Terms and Definitions FRA 2020*. http://www.fao.org/3/I8661EN/i8661en.pdf (June 13, 2019).
Faustmann, Martin. 1849. "Berechnung Des Wertes Welchen Wladboden Sowie Noch Nicht Haubare Holzbestände Für Die Wladwirtschaft Besitzen [Calculation of the Value Which Forest Land and Immature Stands Possess for Forestry]." *Allgemeine Forst- und Jadg-Zeitung* 15: 441–55.
Favero, Alice, and Robert Mendelsohn. 2014. "Using Markets for Woody Biomass Energy to Sequester Carbon in Forests." *Journal of the Association of Environmental and Resource Economists* 1(1/2): 75–95.
Favero, Alice, Robert Mendelsohn, and Brent Sohngen. 2018. "Can the Global Forest Sector Survive 11 °C Warming?" *Agricultural and Resource Economics Review* 47(2): 388–413.
Fernandes, Paulo M et al. 2013. "Prescribed Burning in Southern Europe: Developing Fire Management in a Dynamic Landscape." *Frontiers in Ecology and the Environment* 11(SUPPL. 1).
Ficko, Andrej et al. 2019. "European Private Forest Owner Typologies: A Review of Methods and Use." *Forest Policy and Economics* 99: 21–31.
Galik, Christopher S., and Robert C. Abt. 2016. "Sustainability Guidelines and Forest Market Response: An Assessment of European Union Pellet Demand in the Southeastern United States." *GCB Bioenergy* 8(3): 658–69.
Garcia, Serge, Jens Abildtrup, and Anne Stenger. 2018. "How Does Economic Research Contribute to the Management of Forest Ecosystem Services?" *Annals of Forest Science* 75(2): 53.
Geijer, Erik et al. 2014. "Safeguarding Species Richness vs. Increasing the Use of Renewable Energy—The Effect of Stump Harvesting on Two Environmental Goals." *Journal of Forest Economics* 20: 111–25.
Geijer, Erik, Göran Bostedt, and Runar Brännlund. 2011. "Damned If You Do, Damned If You Do Not-Reduced Climate Impact vs. Sustainable Forests in Sweden." *Resource and Energy Economics* 33(1): 94–106.
Haines-Young, Roy, and Marion B. Potschin. 2018. European Environment Agency *Common International Classification of Ecosystem Services (CICES) V5.1 and Guidance on the Application of the Revised Structure*.
Hall, George R. 1963. "The Myth and Reality of Multiple Use Forestry." *Natural Resources Journal* 2: 276–90.
Hamilton, Serena H et al. 2015. "Integrated Assessment and Modelling: Overview and Synthesis Ofsalient Dimensions." *Environmental Modelling and Software* 64: 215–29.
Hanewinkel, Marc, Susan Hummel, and Axel Albrecht. 2011. "Assessing Natural Hazards in Forestry for Risk Management: A Review." *European Journal of Forest Research* 130(3): 329–51.
Hänninen, Riitta, and A. Maarit I Kallio. 2007. "Economic Impacts on the Forest Sector of Increasing Forest Biodiversity Conservation in Finland." *Silva Fennica* 41(3): 507–23.
Härkönen, S et al. 2019. "A Climate-Sensitive Forest Model for Assessing Impacts of Forest Management in Europe." *Environmental Modelling and Software* 115(August 2018): 128–43.
Harris, G. 2002. "Integrated Assessment and Modelling: An Essential Way of Doing Science." In *Environmental Modelling and Software*, , 201–7.
Hartman, Richard. 1976. "The Harvesting Decision When A Standing Forest Has Value." *Economic Inquiry* XIV(March): 52–58.
Havlík, Petr et al. 2011. "Global Land-Use Implications of First and Second Generation Biofuel Targets." *Energy Policy* 39(10): 5690–5702.
Heckbert, Scott, Tim Baynes, and Andrew Reeson. 2010. "Agent-Based Modeling in Ecological Economics." *Annals of the new york academy of sciences* 1185: 39–53.
Hernández-Morcillo, Mónica, Tobias Plieninger, and Claudia Bieling. 2013. "An Empirical Review of Cultural Ecosystem Service Indicators." *Ecological Indicators* 29: 434–44.
Hourcade, Jean-Charles, Mark Jaccard, Chris Bataille, and Frederic Ghersi. 2011. "Hybrid Modeling: New Answers to Old Challenges Introduction to the Special Issue of The Energy Journal." *The Energy Journal* SI2006(01).

Hugosson, Mårten, and Fredrik Ingemarson. 2004. "Objectives and Motivations of Small-Scale Forest Owners; Theoretical Modelling and Qualitative Assessment." *Silva Fennica* 38(2): 217–31.
Im, Eun Ho, Darius M Adams, and Gregory S Latta. 2007. "Potential Impacts of Carbon Taxes on Carbon Flux in Western Oregon Private Forests." *Forest Policy and Economics* 9(8): 1006–17.
———. 2010. "The Impacts of Changes in Federal Timber Harvest on Forest Carbon Sequestration in Western Oregon." *CANADIAN JOURNAL OF FOREST RESEARCH-REVUE CANADIENNE DE RECHERCHE FORESTIERE* 40(9): 1710–23.
Ince, Peter J. et al. 2008. "Market Impacts of Hypothetical Fuel Treatment Thinning Programs on Federal Lands in the Western United States." *Forest Policy and Economics* 10(6): 363–72.
Ince, Peter J et al. 2011. "U.S. Forest Products Module: A Technical Document Supporting the Forest Service 2010 RPA Assessment.
IPCC. 2018. Ipcc - Sr15 *Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response To*. Geneva.
Janssen, MA, and E Ostrom. 2006. "Empirically Based , Agent-Based Models." *Ecology and Society* 11(2).
Jåstad, Eirik Ogner et al. 2018. "Modelling of Uncertainty in the Economic Development of the Norwegian Forest Sector." *Journal of Forest Economics* 32(May 2017): 106–15.
Johnston, Craig, and G. Cornelis van Kooten. 2014. "Modelling Bi-Lateral Forest Product Trade Flows : Experiencing Vertical and Horizontal Chain." (August).
Johnston, Craig M.T., and G. Cornelis van Kooten. 2016. "Global Trade Impacts of Increasing Europe's Bioenergy Demand." *Journal of Forest Economics* 23: 27–44.
Kallio, A. M I, O. Salminen, and R. Sievänen. 2013. "Sequester or Substitute-Consequences of Increased Production of Wood Based Energy on the Carbon Balance in Finland." *Journal of Forest Economics* 19(4): 402–15.
Kallio, A. Maarit I., Alexander Moiseyev, and Birger Solberg. 2006. "Economic Impacts of Increased Forest Conservation in Europe: A Forest Sector Model Analysis." *Environmental Science and Policy* 9(5): 457–65.
Kallio, A. Maarit I., and Birger Solberg. 2018. "On the Reliability of International Forest Sector Statistics: Problems and Needs for Improvements." *Forests* 8(2): 407.
Kallio, A. Maarit I. 2010. "Accounting for Uncertainty in a Forest Sector Model Using Monte Carlo Simulation." *Forest Policy and Economics* 12(1): 9–16.
Kallio, A. Maarit I, Perttu Anttila, Megan McCormick, and Antti Asikainen. 2011. "Are the Finnish Targets for the Energy Use of Forest Chips Realistic-Assessment with a Spatial Market Model." *Journal of Forest Economics* 17(2): 110–26.
Kallio, A. Maarit I, Riitta Hänninen, Nina Vainikainen, and Sandra Luque. 2008. "Biodiversity Value and the Optimal Location of Forest Conservation Sites in Southern Finland." *Ecological Economics* 67(2): 232–43.
Kallio, A. Maarit I, and Birger Solberg. 2018. "Leakage of Forest Harvest Changes in a Small Open Economy: Case Norway." *Scandinavian Journal of Forest Research* 33(5): 502–10.
Kallio, A Maarit I, Alexander Moiseyev, and Birger Solberg. 2004. "The Global Forest Sector Model EFI-GTM. The Model Structure." *EFI technical report* 15(15): 24.
Kallio, A Maarit I, Birger Solberg, Liisa Käär, and Risto Päivinen. 2018. "Economic Impacts of Setting Reference Levels for the Forest Carbon Sinks in the EU on the European Forest Sector." *Forest Policy and Economics* 92(May): 193–201.
Kangas, Hanna Liisa et al. 2011. "Investments into Forest Biorefineries under Different Price and Policy Structures." *Energy Economics* 33(6): 1165–76.
van Kooten, G. Cornelis, and Craig Johnston. 2016. "The Economics of Forest Carbon Offsets." *Ssrn* (April): 1–20.
Krieger, Douglas J. 2001. *The Economic Values of Forest Ecosystem Services: A Review. The Wilderness Society.*
Kumer, Peter, and Erik Štrumbelj. 2017. "Clustering-Based Typology and Analysis of Private Small-Scale Forest Owners in Slovenia." *Forest Policy and Economics* 80: 116–24.
Kuuluvainen, Jari, Heimo Karppinen, and Ville Ovaskainen. 1996. "Landowner Objectives and Nonindustrial Private Timber Supply." *Forest Science* 42(3): 300–309.
Latta, Gregory, Darius M Adams, Ralph J Alig, and Eric White. 2011a. "Simulated Effects of Mandatory versus Voluntary Participation in Private Forest Carbon Offset Markets in the United States." *Journal of Forest Economics* 17(2): 127–41.
———. 2011b. "Simulated Effects of Mandatory versus Voluntary Participation in Private Forest Carbon Offset Markets in the United States." *Journal of Forest Economics* 17: 127–41.
Latta, Gregory S., Justin S. Baker, and Sara Ohrel. 2018a. "A Land Use and Resource Allocation (LURA) Modeling System for Projecting Localized Forest CO2effects of Alternative Macroeconomic Futures." *Forest Policy and Economics* 87(October 2017): 35–48.
Latta, Gregory S., Hanne K. Sjolie, and Birger Solberg. 2013. "A Review of Recent Developments and Applications of Partial Equilibrium Models of the Forest Sector." *Journal of Forest Economics* 19(4): 350–60.
Latta, Gregory S, Justin S Baker, and Sara Ohrel. 2018b. "A Land Use and Resource Allocation (LURA) Modeling System for Projecting Localized Forest CO2effects of Alternative Macroeconomic Futures." *Forest Policy and Economics* 87: 35–48.
Lecocq, Franck et al. 2011. "Paying for Forest Carbon or Stimulating Fuelwood Demand? Insights from the French Forest Sector Model." *Journal of Forest Economics* 17(2): 157–68.
Li, Ruhong et al. 2008. "Long-Term Effects of Eliminating Illegal Logging on the World Forest Industries, Trade, and Inventory." *Forest Policy and Economics* 10(7–8): 480–90.
Lobianco, Antonello, Sylvain Caurla, Philippe Delacote, and Ahmed Barkaoui. 2016. "Carbon Mitigation Potential of the French Forest Sector under Threat of Combined Physical and Market Impacts Due to Climate Change." *Journal of Forest Economics* 23: 4–26.
Lobianco, Antonello, Philippe Delacote, Sylvain Caurla, and Ahmed Barkaoui. 2015. "The Importance of Introducing Spatial Heterogeneity in Bio-Economic Forest Models: Insights Gleaned from FFSM++." *Ecological Modelling* 309–310: 82–92.

———. 2016. "Accounting for Active Management and Risk Attitude in Forest Sector Models An Impact Study on French Forests." *Environ Model Assess* 21: 391–405.
Mace, Georgina M., Ken Norris, and Alastair H. Fitter. 2012. "Biodiversity and Ecosystem Services: A Multilayered Relationship." *Trends in Ecology & Evolution* 27(1): 19–26.
Maes, Joachim et al. 2012. "Mapping Ecosystem Services for Policy Support and Decision Making in the European Union." *Ecosystem Services* 1(1): 31–39.
Mander, Ülo, Hubert. Wiggering, and Katharina Helming. 2007. Multifunctional Land Use: Meeting Future Demands for Landscape Goods and Services *Multifunctional Land Use: Meeting Future Demands for Landscape Goods and Services*. Springer.
MCPEF. 1993. "RESOLUTION H1 General Guidelines for the Sustainable Management of Forests in Europe." *Second Ministerial Conference on the Protection of Forests in Europe 16-17 June 1993* (June): 1–5.
Mendoza, G. A., and H. Martins. 2006. "Multi-Criteria Decision Analysis in Natural Resource Management: A Critical Review of Methods and New Modelling Paradigms." *Forest Ecology and Management* 230(1–3): 1–22.
Merry, Frank et al. 2009. "Balancing Conservation and Economic Sustainability: The Future of the Amazon Timber Industry." *Environmental Management* 44(3): 395–407.
De Meyer, Annelies, Dirk Cattrysse, Jussi Rasinmäki, and Jos Van Orshoven. 2014. "Methods to Optimise the Design and Management of Biomass-for-Bioenergy Supply Chains: A Review." *Renewable and Sustainable Energy Reviews* 31: 657–70.
Milcu, Andra Ioana, Jan Hanspach, David Abson, and Joern Fischer. 2013. "Cultural Ecosystem Services: A Literature Review and Prospects for Future Research." *Ecology and Society* 18(3): art44.
Moiseyev, Alexander, Birger Solberg, and A. Maarit I. Kallio. 2014. "The Impact of Subsidies and Carbon Pricing on the Wood Biomass Use for Energy in the EU." *Energy* 76: 161–67.
Moiseyev, Alexander, Birger Solberg, A. Maarit I Kallio, and Marcus Lindner. 2011. "An Economic Analysis of the Potential Contribution of Forest Biomass to the EU RES Target and Its Implications for the EU Forest Industries." *Journal of Forest Economics* 17(2): 197–213.
Moiseyev, Alexander, Birger Solberg, Bruce Michie, and A. Maarit I Kallio. 2010. "Modeling the Impacts of Policy Measures to Prevent Import of Illegal Wood and Wood Products." *Forest Policy and Economics* 12(1): 24–30.
Morland, Christian, Franziska Schier, Niels Janzen, and Holger Weimar. 2018. "Supply and Demand Functions for Global Wood Markets: Specification and Plausibility Testing of Econometric Models within the Global Forest Sector." *Forest Policy and Economics* 92: 92–105.
Mosnier, A. et al. 2014. "Modeling Impact of Development Trajectories and a Global Agreement on Reducing Emissions from Deforestation on Congo Basin Forests by 2030." *Environmental and Resource Economics* 57(4): 505–25.
Mustapha, W.F., E. Trømborg, and T.F. Bolkesjø. 2017. "Forest-Based Biofuel Production in the Nordic Countries: Modelling of Optimal Allocation." *Forest Policy and Economics* (September 2016): 1–10.
Niquidet, Kurt, and Devon Friesen. 2014. "Bioenergy Potential from Wood Residuals in Alberta: A Positive Mathematical Programming Approach." *Canadian Journal of Forest Research* 44(12): 1586–94.
Northway, Steven, Gary Q. Bull, and John D. Nelson. 2013. "Forest Sector Partial Equilibrium Models: Processing Components." *Forest Science* 59(2): 151–56.
Okoro, Stanley U., Udo Schickhoff, and Uwe A. Schneider. 2018. "Impacts of Bioenergy Policies on Land-Use Change in Nigeria." *Energies* 11(1): 152.
Pattanayak, Subhrendu K et al. 2004. "Forest Forecasts: Does Individual Heterogeneity Matter for Market and Landscape Outcomes?" *Forest Policy and Economics* 6(3–4): 243–60.
Perez-Garcia, John, Linda A Joyce, Clark S Binkley, and Andrew D McGuire. 1997. "Economic Impacts of Climatic Change on the Global Forest Sector: An Integrated Ecological/Economic Assessment." *Critical Reviews in Environmental Science and Technology* 27(SPEC. ISS.): S123–38.
Perez-Garcia, John, Linda A Joyce, and A. David McGuire. 2002. "Temporal Uncertainties of Integrated Ecological/Economic Assessments at the Global and Regional Scales." *Forest Ecology and Management* 162(1): 105–15.
Peter, Brian, and Kurt Niquidet. 2016. "Estimates of Residual Fibre Supply and the Impacts of New Bioenergy Capacity from a Forest Sector Transportation Model of the Canadian Prairie Provinces." *Forest Policy and Economics* 69: 62–72.
Petucco, Claudio, Antonello Lobianco, and Sylvain Caurla. 2019. "Economic Evaluation of an Invasive Forest Pathogen at a Large Scale: The Case of Ash Dieback in France." *Environmental Modeling and Assessment*.
Pohjola, Johanna, Jani Laturi, Jussi Lintunen, and Jussi Uusivuori. 2018. "Immediate and Long-Run Impacts of a Forest Carbon Policy—A Market-Level Assessment with Heterogeneous Forest Owners." *Journal of Forest Economics* 32: 94–105.
Põllumäe, Priit, Henn Korjus, and Teele Paluots. 2014. "Management Motives of Estonian Private Forest Owners." *Forest Policy and Economics* 42: 8–14.
Prestemon, Jeffrey P., Karen L Abt, and Robert J Huggett. 2008. "Market Impacts of a Multiyear Mechanical Fuel Treatment Program in the U.S." *Forest Policy and Economics* 10(6): 386–99.
Prestemon, Jeffrey P, Karen L Abt, Kevin M Potter, and Frank H Koch. 2013. "An Economic Assessment of Mountain Pine Beetle Timber Salvage in the West." *Western Journal of Applied Forestry* 28(4): 143–53.
Rafal, Chudy et al. 2013. "Modeling the Impacts of EU Bioenergy Demand on the Forest Sector of the Southeast U.S." *Journal of Energy and Power Engineering* 7: 1073–81.
Rogelj, J et al. 2018. "Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development." In *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change,* eds. [Masson-Delmotte, S. Connors V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, and and T. Waterfield (eds.) J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor. In press.

Rougieux, Paul, and Olivier Damette. 2018. "Reassessing Forest Products Demand Functions in Europe Using a Panel Cointegration Approach." *Applied Economics* 50(30): 3247–70.
Samuelson, Paul A. 1952. "Spatial Price Equilibrium and Linear Programming." *American Economic Review* 42(3): 283–303.
Schleupner, Christine, and Uwe A Schneider. 2010. "Effects of Bioenergy Policies and Targets on European Wetland Restoration Options." *Environmental Science and Policy* 13(8): 721–32.
———. 2013. "Allocation of European Wetland Restoration Options for Systematic Conservation Planning." *Land Use Policy* 30: 604–14.
Schwarzbauer, Peter, and Ewald Rametsteiner. 2001. "The Impact of SFM-Certification on Forest Product Markets in Western Europe - An Analysis Using a Forest Sector Simulation Model." *Forest Policy and Economics* 2(3–4): 241–56.
Sedjo, Roger A., and Brent Sohngen. 2012. "Carbon Sequestration in Forests and Soils." *Ssrn*.
Shabani, Nazanin, Shaghaygh Akhtari, and Taraneh Sowlati. 2013. "Value Chain Optimization of Forest Biomass for Bioenergy Production: A Review." *Renewable and Sustainable Energy Reviews* 23: 299–311.
Sievanen, Leila, Lisa M Campbell, and Heather M Leslie. 2012. "Challenges to Interdisciplinary Research in Ecosystem-Based Management." *Conservation Biology* 26(2): 315–23.
Sjolie, H K, Greg S Latta, and Birger Solberg. 2013. "Potentials and Costs of Climate Change Mitigation in the Norwegian Forest Sector - Does Choice of Policy Matter?" *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere* 43(6): 589–98.
Sjølie, Hanne K., Greg S. Latta, and Birger Solberg. 2014. "Impacts of the Kyoto Protocol on Boreal Forest Climate Change Mitigation." *Annals of Forest Science* 71(2): 267–77.
Sjølie, Hanne K., Gregory S. Latta, Darius M. Adams, and Birger Solberg. 2011. "Impacts of Agent Information Assumptions in Forest Sector Modeling." *Journal of Forest Economics* 17(2): 169–84.
Sjølie, Hanne K., and Birger Solberg. 2011. "Greenhouse Gas Emission Impacts of Use of Norwegian Wood Pellets: A Sensitivity Analysis." *Environmental Science & Policy* 14(8): 1028–40.
Sjølie, Hanne K, Greg S Latta, Terje Gobakken, and Birger Solberg. 2011. "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*.
Sjølie, Hanne K, Erik Trømborg, Birger Solberg, and Torjus F Bolkesjø. 2010. "Effects and Costs of Policies to Increase Bioenergy Use and Reduce GHG Emissions from Heating in Norway." *Forest Policy and Economics* 12(1): 57–66.
Solberg, Birger. 1986. "Forest Sector Simulation Models as Methodological Tools in Forest Policy Analysis (Norway)." *Silva Fennica* 20(4): 419–27.
Solberg, Birger, Alexander Moiseyev, and A.Maarit I. Kallio. 2003. "Economic Impacts of Accelerating Forest Growth in Europe." *Forest Policy and Economics* 5(2): 157–71.
Sturrock, R. N. et al. 2011. "Climate Change and Forest Diseases." *Plant Pathology* 60(1): 133–49.
Sun, Changyou. 2016. "Timber Market Recovery after a Hurricane." *Forest Science* 62(6): 600–612.
Sun, Lili, and Bryan E.C. Bogdanski. 2017. "Trade Incentives for Importers to Adopt Policies to Address Illegally Logged Timber: The Case of Non-Tropical Hardwood Plywood." *Journal of Forest Economics* 27: 18–27.
Tardieu, Léa. 2017. "The Need for Integrated Spatial Assessments in Ecosystem Service Mapping." *Review of Agricultural, Food and Environmental Studies* 98(3): 173–200.
Tardieu, Léa, and Laëtitia Tuffery. 2019. "From Supply to Demand Factors: What Are the Determinants of Attractiveness for Outdoor Recreation?" *Ecological Economics* 161: 163–75.
Tavoni, Massimo, Brent Sohngen, and Valentina Bosetti. 2007. "Forestry and the Carbon Market Response to Stabilize Climate." *Energy Policy* 35(11): 5346–53.
TEEB. 2010. *The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of TEEB*.
Toppinen, Anne, and Jari Kuuluvainen. 2010. "Forest Sector Modelling in Europe-the State of the Art and Future Research Directions." *Forest Policy and Economics* 12(1): 2–8.
Trømborg, Erik, Torjus Folsland Bolkesjø, and Birger Solberg. 2007. "Impacts of Policy Means for Increased Use of Forest-Based Bioenergy in Norway-A Spatial Partial Equilibrium Analysis." *Energy Policy* 35(12): 5980–90.
Trømborg, Erik, and Hanne K Sjølie. 2011. "Data Applied in the Forest Sector Models NorFor and NTMIII." *INA fagrapport. Department of Ecology and Natural Resource Management Norwegian University of Life Sciences* 17.
Turner, James A et al. 2007. "Modelling the Impact of the Exotic Forest Pest Nectria on the New Zealand Forest Sector and Its Major Trading Partners." *New Zealand Journal of Forestry Science* 37(3): 383–411.
Uhde, Britta, Andreas Hahn, Verena C. Griess, and Thomas Knoke. 2015. "Hybrid MCDA Methods to Integrate Multiple Ecosystem Services in Forest Management Planning: A Critical Review." *Environmental Management* 56(2): 373–88.
Wear, David N, and John W Coulston. 2019. "Specifying Forest Sector Models for Forest Carbon Projections." *Journal of Forest Economics* 34(1–2): 73–97.
White, Eric M. et al. 2013. "Biomass Production from the U.S. Forest and Agriculture Sectors in Support of a Renewable Electricity Standard." *Energy Policy* 58: 64–74.
Yousefpour, Rasoul et al. 2018. "Realizing Mitigation Efficiency of European Commercial Forests by Climate Smart Forestry." *Scientific Reports* 8(1): 1–11.
Yu, Chin-Hsien, Bruce McCarl, Chin-Hsien Yu, and Bruce A. McCarl. 2018. "The Water Implications of Greenhouse Gas Mitigation: Effects on Land Use, Land Use Change, and Forestry." *Sustainability* 10(7): 2367.
Zhang, Xiaobiao et al. 2016. "Eliminating Illegal Timber Consumption or Production: Which Is the More Economical Means to Reduce Illegal Logging?" *Forests* 7(9).

Chapter 3

Landscape implications of managing forests for carbon sequestration

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Abstract

We explore the implications of managing forests for the dual purpose of sequestering carbon and producing timber, using a model of the forest sector that includes a Hartman-based representation of forest owners' behaviour as well as heterogeneity in environmental conditions. We focus on France, where recent policies aim at increasing the carbon sink and where the diversity of forests make an analysis of spatial dynamics relevant, and we use recent estimates of the shadow price of carbon consistent with the country's climate commitments. Results suggest that forests may sequester up to 550 MtCO2eq by 2100, driven by changes in harvest levels and species choice, while rotation lengths increase overall. A spatial analysis reveals a high spatial variability for these trends, highlighting the importance of considering the local context. Changes in investment patterns affect the spatial distribution of forest cover types: by the end of the century, a majority of regions comprise a larger share of older, multiple-species and mixed-structure forests. While such an evolution may present benefits in terms of biodiversity, ecosystem services provision and resilience, it raises questions regarding the adequacy of such developments with current forest policy, which also aims at increasing harvest levels. An overall mitigation strategy for the forest sector would likely include incentives to energy and material substitution in downstream industries, which we did not consider and may interact with sequestration incentives.

1. Introduction

Reaching climate mitigation objectives requires immediate action (IPCC 2018), to which the forest sector can be an important contributor (Canadell and Raupach 2008; M. Eriksson 2015; Riahi et al. 2017; Tavoni, Sohngen, and Bosetti 2007). Wood-based products can substitute for more climate intensive materials to produce energy or to be used in construction (Birdsey et al. 2018; L. O. Eriksson et al. 2012), and forests also sequester carbon *in situ*, i.e. in biomass and soils, removing carbon from the atmosphere (Sedjo and Sohngen 2012). Such contributions from forestry have been increasingly recognized and encouraged in policy frameworks (e.g. European Parliament, 2018; MTES, 2018; UNFCCC, 2015).

Because forest and climate policies are often regulated at national and supranational levels, and due to the complexity of the forest sector, there is a need for large-scale assessments of mitigation possibilities. These have largely focused on the implications and feasibility of increased bioenergy production (e.g. Buongiorno et al., 2011; Galik et al., 2015; Lauri et al., 2014; Moiseyev et al., 2013; Valade et al., 2018), but sequestration also has a strong potential to offset emissions and may be used alongside substitution strategies to effectively mitigate climate change (Baker et al. 2019; Canadell and Raupach 2008; M. Eriksson 2015; Favero, Mendelsohn, and Sohngen 2017; Vass and Elofsson 2016).

In recent years, emission reductions generated by forestry projects have increasingly been traded on voluntary and compliance carbon markets, which constitutes an opportunity for forest owners to receive compensation for the environmental service provided in carbon storage (van Kooten and Johnston 2016). However, improving sequestration requires changes in forest management, which in turn may locally affect landscapes and the provision of ecosystem services (Adams et al. 2011; Jeffrey Englin and Callaway 1995; Freedman, Stinson, and Lacoul 2009; Gutrich and Howarth 2007a; Im, Adams, and Latta 2007). Besides, sequestration potentials and costs vary across space, and incentives may induce different responses from forest owners (Adams et al. 2011; van Kooten, Laaksonen-Craig, and Wang 2009; Yousefpour et al. 2018). Large-scale economic models of the forest sector often overlook or simplify management dynamics and environmental conditions. To develop a thorough understanding of the opportunities provided by sequestration incentives as well as of their implications, assessments should consider feedbacks between timber markets, forest resources and forest management, while taking into account local context.

Our objective is to explore dynamics in the forest sector when forests are managed for the joint production of timber and *in situ* carbon sequestration, focusing on the case of France. Following international commitments, the country seeks to reach carbon neutrality by 2050, and policies put a strong emphasis on mobilizing the forest sector (MAA, 2016; MTES, 2017; 2018). Efforts will be accounted for against a reference level (CITEPA et al. 2019), and a certification standard aimed at voluntary carbon markets has recently been approved and includes several protocols for forest-based sequestration projects (JORF 2018). French forests cover 16 million hectares (1/3 of the territory) and encompass a broad range of forest types and management regimes, from Mediterranean shrublands to beech-oak forests to maritime pine (*Pinus pinaster* Ait.) plantations, spanning diverse biophysical and climatic conditions. This diversity, together with the existence of a strong political will for forest-based mitigation, make France a good example for assessing spatial dynamics.

We use a model of the French forest sector comprising a market model for timber products, a forest resource component and a forest management model. We proceed by scenario analysis and compare a scenario where forests are only managed for timber production to scenarios where *in situ* carbon sequestration is also an objective. This is performed by integrating Hartman's (1976) optimal rotation model, usually used at the forest or stand scale, and attributing a monetary value to sequestered carbon using recent estimates of the shadow price of carbon in France (Quinet 2019). We contribute to the literature by assessing potential for *in situ* sequestration at a spatially disaggregated scale, taking into account discrepancies across and within regions, but also by stressing the importance of management adaptations and their long-term implications for forest landscapes.

We first provide an overview of the literature, focusing on bio-economic modelling studies. Second, we outline the model used in this study and describe our scenarios. Third, we present results, putting the emphasis on spatial dynamics, forest management and their long-term implications for landscapes and carbon stocks. Fourth, we compare our results to the literature and discuss their policy implications, as well as the potential limits of our approach.

2. Literature review

Large-scale assessments of mitigation strategies in the forest sector are often carried out with simulation models such as forest sector models, i.e. partial equilibrium models that capture feedbacks between timber markets and forest resources (Latta, Sjolie, and Solberg 2013). In this field, a major focus has been on assessing the potential for producing bioenergy from forest biomass (Riviere, Caurla, and Delacote 2020). More recently, research has turned to assessing combinations of substitution and sequestration strategies, and recent results estimate that an optimal mitigation strategy would likely include a combination of both due to potential synergies (Baker et al. 2019; Favero and Mendelsohn 2014; Favero, Mendelsohn, and Sohngen 2017; Kim et al. 2018). However, the question remains debated. For example, Vass and Elofsson (2016) find that expanding sequestration at the expense of bioenergy production may reduce the cost of reaching the EU's 2050 emissions reduction target, while Eriksson (2015) suggests sequestration performs better globally due to avoided emissions from bioenergy not being able to offset increased harvests, an issue still debated in the literature (e.g. Birdsey et al., 2018; McKechnie et al., 2011; Valade et al., 2018).

At the level of forest owners, carbon sequestration is increasingly incentivized via the generation of forest carbon offsets, i.e. certified emission reductions resulting from forest management practices. These broadly fall within the more general scope of payments for environmental services (West et al. 2019; Wunder 2015) and, when certified, can be sold on compliance or voluntary carbon markets where buyers are required or wish to compensate their emissions (Kollmuss et al. 2010; van Kooten and Johnston 2016). In recent years, an increasing number of compliance markets have included offsets from forestry projects. These include, among others, emission-trading schemes in California, New Zealand and Australia (Ecosystem Marketplace 2017). At the same time, certification standards aimed at voluntary carbon markets are being set up in many countries (Cevallos, Grimault, and Bellassen 2019), including France (JORF 2018). Forestry practices that increase carbon stocks and are eligible include avoided deforestation (VCS, 2015) and afforestation-reforestation (Gold Standard 2017), but also extended rotations (VCS 2012), forest conversion (CNPF 2019) and improved forest management (ACR 2018). Methodologies may also recognize the non-climate benefits (e.g. biodiversity, ecosystem services provision) of management practices aiming at producing carbon offsets (Simonet, Delacote, and Robert 2016).

A few large-scale simulation experiments have focused on such incentives. Buongiorno & Zhu (2013) show that implementing offset payments at 50$/t$CO_2$ could increase global sequestration by 9% by 2030 while bearing risks of leakage when applied unilaterally. Guo and Gong (2017) show that sequestration payments in Sweden would increase the carbon sink, especially in the medium-term, at the cost of a decrease in consumer surplus, i.e., the benefit consumers derive from buying timber on the market. Lecocq et al. (2011) come to a similar conclusion for France and show that, in the short term, sequestration payments are preferable to bioenergy subsidies. Pohjola et al. (2018) perform an assessment for Finland and include a subsidy to manufacturers of long-lived wood products. They determine that even low carbon prices can yield lasting climate benefits, and highlight the importance of combining a market model to realistic descriptions of owners' behaviours. Many of these studies focus on downstream impacts on forest industries, incorporate simplified descriptions of forest resources, or do not fully integrate management adaptations, which impedes taking into account the local determinants and implications of sequestration incentives.

Part of the response may be found using models with endogenous management. For example, in Oregon, Im et al. (2007) show that a sequestration subsidy would alter management and harvest decisions varyingly across ownership categories, Latta *et al.* (2016) highlight a shift towards simpler management and reductions in the loss of forestland to other land uses, and Adams *et al.* (2011) highlight that responses would vary markedly across US regions due to local context. Such studies are rarer in Europe. Their closest relative is the Norwegian assessment by Sjolie et al. (2013), who apply a carbon tax to all carbon fluxes within the forest sector. They highlight the importance of considering not only management adaptations, but also changes in harvest levels and wood uses.

Another strand of literature focuses on the stand/forest level and uses optimal rotation models derived from Hartman (1976). These studies consider owners that manage their forests to both provide timber and amenity benefits, which, when not priced, requires the use of economic valuation techniques (Amacher, Ollikainen, and Koskela 2010). Applications to carbon storage started with the seminal works of Englin and Callaway (1993, 1995) and van Kooten et al. (1995), and seek to explore the implications of sequestration incentives for forest management at fine scales, usually focusing on specific tree species and management regimes and using site-specific growth functions or growth simulators (e.g. Alavalapati and Stainback, 2005; Gutrich and Howarth, 2007a; Olschewski and Benítez, 2010; Pohjola and Valsta, 2007; Sohngen and Brown, 2008; West et al., 2019). When climate benefits from carbon storage are internalised, harvests are generally postponed, land value increases, and the profitability of different species and management operations may change. Issues associated to sequestration payments include the choice of a reference against which to compare carbon storage, heterogeneity across space, risks of non-permanence and the form taken by payments (Gren and Zeleke 2016; van Kooten and Johnston 2016; Lintunen, Laturi, and Uusivuori 2016; West et al. 2019). While they consider the local context and provide a detailed overview of management practices, such studies lack the generalisation power of large-scale simulations and usually treat timber markets as exogenous.

We seek to fill a gap in the literature by integrating a heterogeneous model of forest management based on Hartman's optimal rotation framework into a large-scale forest sector model. This enables to not only assess changes in forest management, but also to assess their landscape impacts over time, as owners change the structure and composition of their forests, while still capturing feedbacks with industries. While previous studies mostly focus on the downstream forest sector, we instead focus on upstream dynamics, and our study comes as a complement to previous French assessments (Caurla et al. 2013; Lecocq et al. 2011). In particular, we use a model with a spatial resolution at the level of 8km-wide pixels, with heterogeneous environmental conditions, and we put a strong emphasis on spatial variability. We use recent estimates of the shadow price of carbon, consistent with France's climate commitments, which leads us to consider higher values than usually found in the literature. In a context where an increasing number of markets for emissions reductions incorporate forest-based offsets, our exercise questions the design of sequestration incentives aimed at owners, in particular regarding the role played by local context and the potential impacts of management adaptations on landscapes.

3. Material and methods

3.1. FFSM, an optimization model of the French forest sector

We use the French Forest Sector Model (FFSM), a bio-economic model of the French forest sector (Caurla et al. 2010; Lobianco et al. 2015; Lobianco, Delacote, et al. 2016). The model comprises three modules (Figure 3.1), is recursive and uses yearly time-steps. The market module is a partial equilibrium model of timber markets employing the spatial price equilibrium framework (Samuelson 1952). Quantities produced, consumed, traded and prices are endogenously determined for 3 primary products and 6 transformed products across 12 regions by maximizing total economic surplus net of transportation costs. Timber supply is elastic to prices and available timber volumes, and the manufacturing of primary products into transformed products is represented as a set of input-output processes. Domestic products are modelled as imperfect substitutes to international products (Armington 1969; Sauquet et al. 2011).

The forest dynamics module is a transition matrix model based on Wernsdörfer *et al.* (2012) where forest inventory (i.e., timber volumes and forest areas) is represented at the scale of 8km pixels and calibrated using national forest inventory data. The module distinguishes between 13 diameter classes, three categories of species composition and three forest structures. Forests are categorized as mixed when both coniferous and broadleaf species make up more than 15% of forest cover, and are otherwise categorized as either broadleaf or coniferous. Forests are categorized as intermediate structure when both coppice and higher strata make up more than 25% of forest cover, and are otherwise categorized as high forests or coppices. Due to data quality or availability, some categories are not used or do not exist (e.g., coniferous coppices). Forest growth is modelled through diameter-class dynamics where each strata is assigned a time of passage to the next diameter class. Growth conditions are heterogeneous across space and, at the beginning of the simulation, each pixel is assigned growth multipliers sampled from a regional-level distribution (Lobianco et al. 2015). Carbon stocks and fluxes in forest biomass and timber products are tracked in a carbon accounting module (Lobianco *et al.*, 2016).

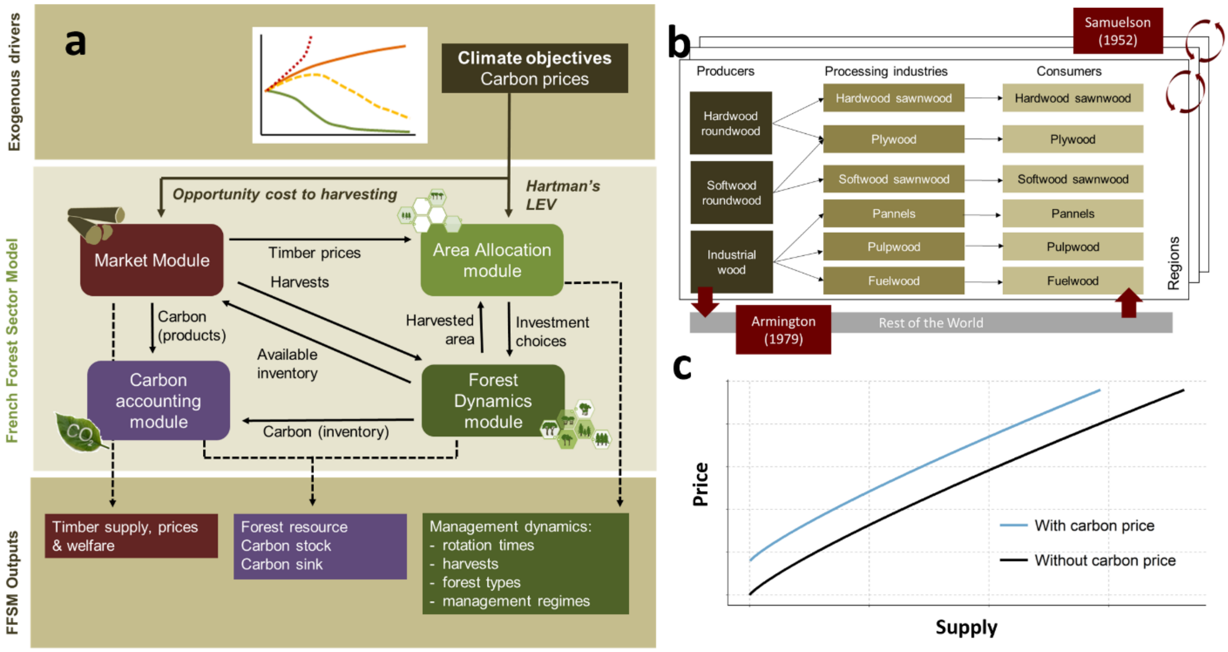


Figure 3. 1 – Overview of the French Forest Sector Model. (a) General model structure and drivers for the current study. (b) Timber products in the market module. (c) Illustration of a supply shift. More details about the model are available at https://ffsm-project.org/wiki/en/home.

The area allocation module is a pixel-level, heterogeneous model of forest management where each pixel is assumed to be managed by a representative forest owner. Following each final harvest, a certain amount of area is freed. For each forest type available, the model computes expected returns from timber sales by solving a "Faustmannian" optimal-rotation problem, and land is allocated to the forest type with highest expected returns from timber. Since growth rates are different across pixels and economic conditions across regions, each forest owner is faced with a unique situation (Lobianco et al. 2015; Lobianco, Delacote, et al. 2016).

3.2. Modifications brought for the current study

Our approach relies on comparing a baseline scenario where forests are only managed for timber production to alternative scenarios where forest owners take into account sequestration benefits when making decisions, hence carbon storage is also an objective. A monetary value (hereafter, carbon price) is subsequently assigned to carbon stored based on the shadow price of carbon in France (Quinet 2019). While other contributions seek to assess the overall mitigation potential of the forest sector through sectoral measures (e.g. Caurla et al., 2013a), we focus on the owner level and do not model incentives in downstream industries.

In the area allocation module, in order to account for sequestration benefits in owners' decisions, the optimal rotation problem is reformulated based on Hartman's (1976) model for non-timber amenities. In the literature, two applications to carbon sequestration are found: the carbon subsidy/tax policy and the carbon rent policy. Both frameworks are consistent with assuming that owners can sell forest offsets onto carbon markets and lead to similar outcomes (Lintunen, Laturi, and Uusivuori 2016). We employ the carbon rent framework, where owners receive yearly carbon payments (rents) that apply to the whole carbon stock for as long as it remains in the forest. In a discrete time case where an investment choice is made at year 0, the Land Expectation Value (*LEV)* is given by:

$$[7] \quad LEV(T) = \frac{p_T q_T (1+r)^{-T} + \alpha v_T P_c (1+r)^{-T} + \sum_{t=1}^{T} r P_c v_t (1+r)^{-t}}{1-(1+r)^{-T}}$$

where q is the quantity of timber products harvested, p is the price of timber products, v is the volume of carbon, P_c the carbon price, r the discount rate, T the rotation time, and $\propto$ a parameter indicating the durability of carbon storage in wood products. The quantity $p_T q_T (1+r)^{-T}$ corresponds to the value of timber sales after harvest, $\sum_{t=1}^{T} r P_c v_t (1+r)^{-t}$ to the stream of yearly carbon rents, and $\alpha v_T P_c (1+r)^{-T}$ to an end-term payment for carbon sequestered in harvested wood products. Certification methodologies for forest offsets may or may not include carbon in products pools, or label them as optional (e.g. VCS, 2017). In our analysis, we assume all carbon is released at harvest, and only carbon stored in forest biomass is valued. Because not all carbon harvested is immediately released, this approach underestimates the potential climate benefits of forest management (West et al. 2019).

In the FFSM, harvests are short-term decisions that derive from timber supply at market equilibrium in the market module. Carbon rents induce an opportunity cost to timber supply equal to the foregone carbon payment per unit of harvested timber, and is modelled as an increase in marginal harvesting costs (Buongiorno and Zhu, 2013; Lecocq et al., 2011). The demand component of the model remains unaffected.

Carbon sequestration may be unintentional and result from activities that do not aim at mitigating climate change. If the social planner's objective is climate change mitigation, only additional carbon should be counted, i.e. carbon that would not have been sequestered in the absence of incentives. Most offset schemes are also likely to include an additionality condition for practical reasons, such as cost reduction or to limit the amount of offsets generated (Lintunen *et al.*, 2016). Therefore, in our scenarios, only additional carbon is attributed a monetary value, and, for every decision, the reference used is "based on harvest behavior without the forest-carbon policy" (Lintunen, 2016), i.e. "Faustmannian" management.

3.3. Scenario building

We use carbon prices based on the shadow price of carbon in France, estimated in a report commissioned by the French government to guide public policy, calibrate incentives, and provide an indicator of the value French society should attribute to actions that reduce greenhouse gases emissions (Quinet 2019). Based on a "zero net emissions" target for 2050, the report estimates the shadow price of carbon through a combination of integrated assessment models of the energy-climate-economy system following a cost-effectiveness approach, and prospective analysis.

In addition to a baseline scenario ("BAU") where the carbon price is set to 0, we build four scenarios (Figure 3.2). In "MAIN", we use the carbon price path from the report. From 87€/tCO2eq in 2020, carbon prices rise to 250€/tCO2eq in 2030 and 775€/tCO2eq in 2050. Two other scenarios use the lower ("LOW") and higher ("HIGH") bound values of 600€/tCO2eq and 900€/tCO2eq for 2050. In order for scenarios to be differentiated from one another from the beginning of the simulation, the LOW scenario starts at 60€/tCO2eq, while the HIGH scenario starts at 125€/tCO2eq.

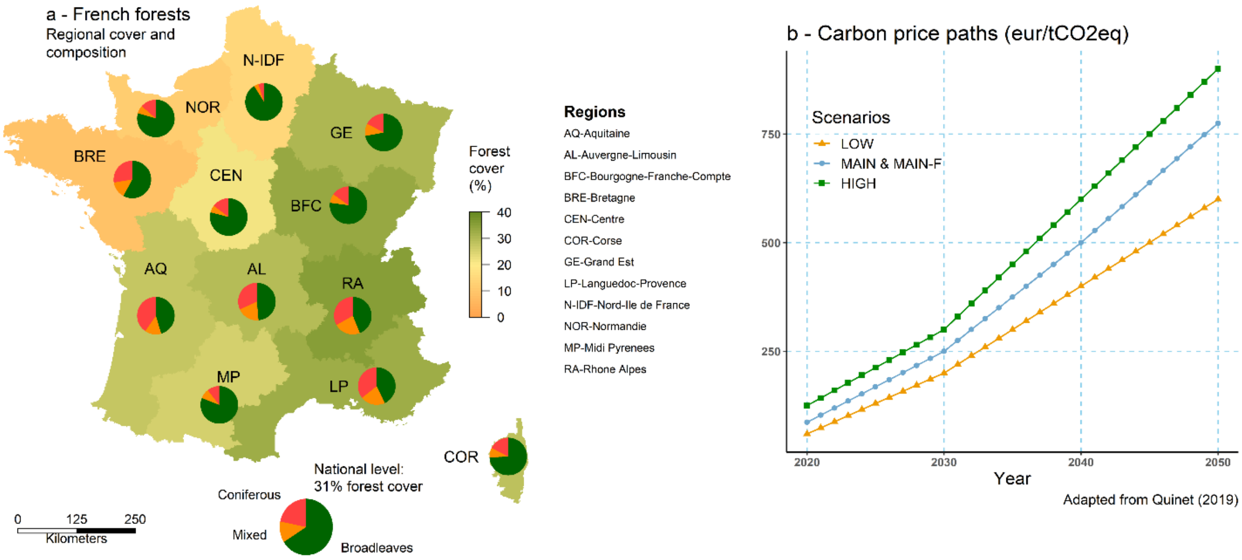


Figure 3.2 – Illustration of the study case: (a) overview of French forests in the FFSM and (b) carbon price paths used in the simulations.

In LOW, MAIN and HIGH, markets can adjust (i.e., wood uses and harvest levels can change), and management decisions follow Hartman's (1976) model. We also build a scenario ("MAIN-F") where market adjustments are still possible but where forest owners' management decisions do not take into account sequestration benefits and follow the classical Faustmann model. MAIN-F uses the same carbon prices as MAIN. MAIN and MAIN-F will be compared to assess the importance of considering management adaptations and to evaluate the impacts of these adaptations on forest landscapes over time.

4. Results

4.1. Market dynamics

Market impacts of sequestration policies have been discussed in previous contributions (e.g., Buongiorno and Zhu 2013; Lecocq *et al.*, 2011; Pohjola *et al.*, 2018), and we only review them shortly (Table 1, more disaggregated results are also available as an online supplementary material). In all scenarios where forests are managed for carbon sequestration, the supply of primary products decreases compared to BAU. This decrease becomes more important as carbon prices rise over time, and concomitantly, product prices increase. For example, in MAIN, the supply of hardwood roundwood is on average 0.68% lower than in BAU for the period 2020-2060, while it is 1.04% lower for the period 2061-2100. At the same time, prices increase by 5.8% and 9.62% respectively. Industrial wood is consistently more affected than hardwood roundwood (e.g., -3.01% supply and +10.33% prices for the period 2020-2060), while softwood roundwood is less affected than both industrial wood and hardwood roundwood. Exports decrease for all primary products. Again, this decrease is especially strong for industrial wood (e.g., -18.84% in the period 2020-2060) and hardwood roundwood (-9.66%), while it remains moderate for softwood roundwood (-2.94%). At the same time, there is a minor increase in imports of transformed products (e.g., +0.59% and +0.99% in 2020-2060 and 2061-2100 respectively). Even though supply decreases for all products, producer surplus (i.e. the benefit producers derive from selling timber on the market) increases due to higher prices, while consumer surplus decreases, the resulting change in total economic surplus being negative. These trends are consistent across scenarios and are positively related to carbon prices. Impacts are more severe in HIGH, where e.g. product supply is 0.45% lower on average (over the whole simulation) than in MAIN, across all products. On the contrary, they are less severe in LOW, with e.g. product supply being 0.58% higher than in MAIN. Differences between results in MAIN and MAIN-F are anecdotal.

Table 3.1 - Market impacts. Values are reported as averages over periods 2020-2060 (1) and 2061-2100 (2) and changes are calculated against BAU. Products are hardwood roundwood (HW), industrial wood (IW), softwood roundwood (SW) and transformed products (TP).

Variable	Products	Period	BAU	MAIN-F		LOW		MAIN		HIGH	
Supply (Mm^3)	HW	1	5,44	5,4	(-0.68%)	5,41	(-0.53%)	5,4	(-0.68%)	5,4	(-0.8%)
		2	5,62	5,56	(-1.09%)	5,57	(-0.79%)	5,56	(-1.04%)	5,55	(-1.22%)
	IW	1	39,5	38,32	(-3.01%)	38,57	(-2.36%)	38,32	(-3.01%)	38,1	(-3.55%)
		2	40,78	38,71	(-5.07%)	39,23	(-3.81%)	38,75	(-4.97%)	38,41	(-5.8%)
	SW	1	21,39	21,32	(-0.33%)	21,33	(-0.27%)	21,32	(-0.34%)	21,31	(-0.4%)
		2	22,14	22,09	(-0.24%)	22,01	(-0.6%)	22	(-0.65%)	21,99	(-0.68%)
Prices (€/m^3)	HW	1	101,75	107,67	(+5.82%)	106,4	(+4.57%)	107,66	(+5.8%)	108,73	(+6.86%)
		2	84,39	92,74	(+9.89%)	90,59	(+7.35%)	92,51	(+9.62%)	93,86	(+11.22%)
	IW	1	30,37	33,5	(+10.33%)	32,81	(+8.04%)	33,5	(+10.33%)	34,1	(+12.31%)
		2	27,1	31,68	(+16.9%)	30,56	(+12.74%)	31,68	(+16.89%)	32,5	(+19.92%)
	SW	1	75,21	76,5	(+1.71%)	76,24	(+1.36%)	76,53	(+1.74%)	76,76	+(2.05%)
		2	68,81	70,14	(+1.93%)	70,59	(+2.6%)	70,92	(+3.07%)	71,15	(+3.41%)
Exports (Mm^3)	HW	1	1,66	1,5	(-9.66%)	1,53	(-7.64%)	1,5	(-9.66%)	1,47	(-11.31%)
		2	2,27	1,97	(-13.43%)	2,04	(-10.34%)	1,97	(-13.32%)	1,92	(-15.34%)
	IW	1	3,43	2,78	(-18.85%)	2,91	(-15.1%)	2,78	(-18.84%)	2,68	(-21.81%)
		2	4,6	3,38	(-26.69%)	3,63	(-21.09%)	3,38	(-26.64%)	3,21	(-30.38%)
	SW	1	1,61	1,57	(-2.94%)	1,58	(-2.3%)	1,57	(-2.94%)	1,56	(-3.45%)
		2	1,86	1,8	(-3.19%)	1,81	(-2.5%)	1,8	(-3.24%)	1,79	(-3.75%)
Imports (Mm^3)	TP	1	8,82	8,87	(+0.59%)	8,86	(+0.46%)	8,87	(+0.59%)	8,88	(+0.7%)
		2	8,39	8,46	(+0.94%)	8,45	(+0.77%)	8,47	(+0.99%)	8,48	(+1.15%)
Producer surplus (M€)		1	1885	1941	(+2.95%)	1929	(+2.31%)	1941	(+2.96%)	1952	(+3.52%)
		2	1832	1891	(+3.24%)	1882	(+2.75%)	1897	(+3.57%)	1908	(+4.18%)
Consumer surplus (M€)		1	6101	6022	(-1.3%)	6038	(-1.02%)	6021	(-1.3%)	6007	(-1.54%)
		2	6207	6082	(-2.03%)	6103	(-1.68%)	6074	(-2.15%)	6053	(-2.48%)

4.2. Carbon dynamics

In BAU, *in situ* carbon stocks (i.e., the total amount of carbon stored in forest biomass at a given moment) increase nationwide from 5.24 GtCO2eq in 2020 to 10.1 GtCO2eq in 2100. In all other scenarios, carbon rents lead to increases in *in situ* carbon stocks, as seen on Figure 3.3a (solid line). By 2050, *in situ* stocks are 55-80 MtCO2eq higher than in BAU, and by 2100, they are 390-550 MtCO2eq higher. Increases in the short to medium term are mostly due to decreased harvests. In the medium to long term, annual sequestration becomes higher in MAIN than in MAIN-F, where forest management does not take into account the value associated to sequestration benefits. These differences are due to changes in replanting choices and, by 2100, in situ stocks contain 60 MtCO2eq more in MAIN than in MAIN-F. Carbon stocks in timber products are lower in all scenarios where forests are managed for carbon sequestration compared to BAU, e.g. 3.8-5.4% lower in 2100. When compared to carbon gains in forest biomass (dashed line) this loss remains limited.

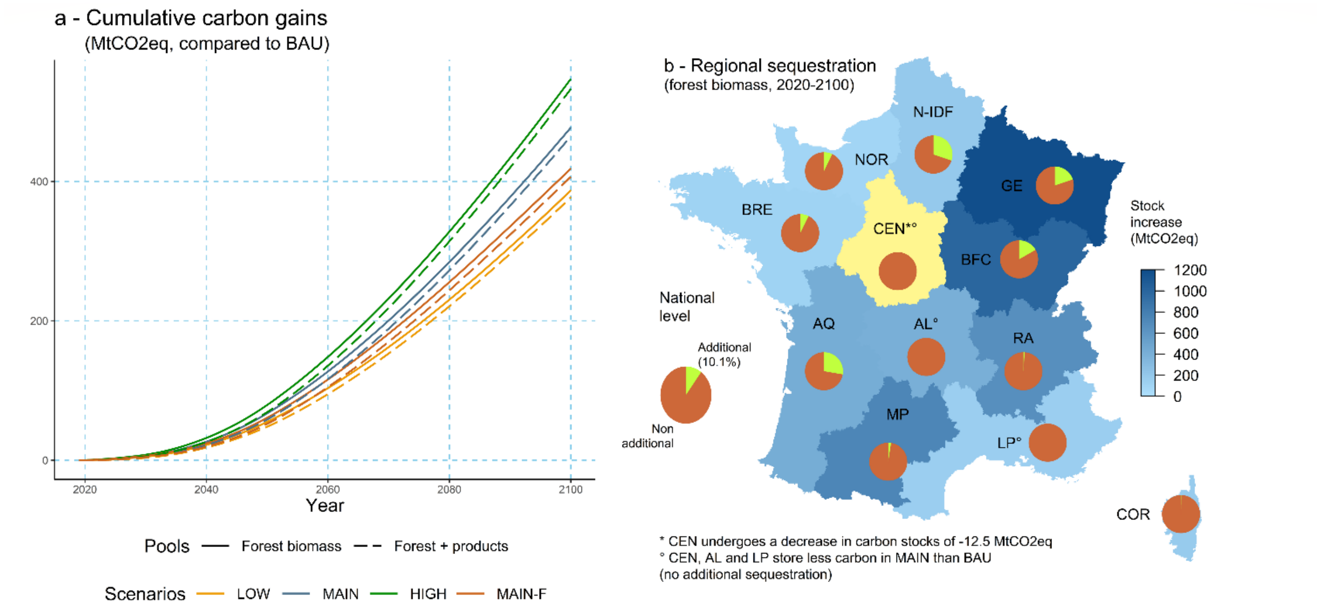


Figure 3.3 – Carbon dynamics at the national and regional levels: (a) cumulative carbon gains compared with BAU and (b) regional sequestration dynamics from 2020 to 2100 in MAIN.

These trends hide significant regional differences. Figure 3.3b displays, for scenario MAIN, regional increases in *in situ* carbon stocks from 2020 to 2100, as well as the share that is additional compared to BAU. Four regions show very high increases in carbon stocks: GE, BFC, MP and RA. However, not all of it is additional when compared to BAU. In the former two, 20% and 17% of stock increases come in addition to stock increases in BAU over the same period, while only 2.4% and 1% is additional in the latter two, for a national average of 10.1%. On the contrary, N-IDF and AQ, despite more moderate increases in carbon stocks, report 30% and 28% of additionality respectively. A similar situation, albeit to a lesser degree, is found in BRE and NOR. Against the general trend, CEN undergoes a decrease in carbon stocks, and CEN, AL and LP store less carbon in MAIN than in BAU, and there is no additional sequestration.

4.3. Harvest levels

At the national level, harvested volumes decrease for all scenarios compared to BAU, and the mean decrease over the simulation ranges from -3.8% in LOW to -5.6% in HIGH. As seen for MAIN on Figure 3.4 (solid black line), this decrease is low at first, and increases as carbon prices rise. Harvest decreases most for broadleaf forests and mixed high forests, while coniferous high forests and mixed forests with intermediate structures are less impacted (Table 3.2). This overall trend hides differences across regions: eight regions show decreases in harvests throughout the simulation, while harvests increase slightly in 3 regions (Figure

3.4). This spatial discrepancy is a consequence of two opposite mechanisms. First, the opportunity cost to harvests impacts industrial wood the most, followed by hardwood, increasing the cost of supplying such timber. Regions with large areas of forests contributing to this production, such as GE, BFC and MP, undergo large reductions in harvests. Following the spatial market equilibrium, products are imported from other regions and from abroad to meet demand in these regions, which results in, broadly speaking, a form of regional specialization. The cost of supplying industrial wood increases relatively less in regions such as CEN and LP, where harvests increase by up to 4-5% compared to BAU, and these regions export pulpwood and panels to other French regions, primarily BFC, GE and N-IDF, while AL exports pulpwood and softwood to BFC and BRE.

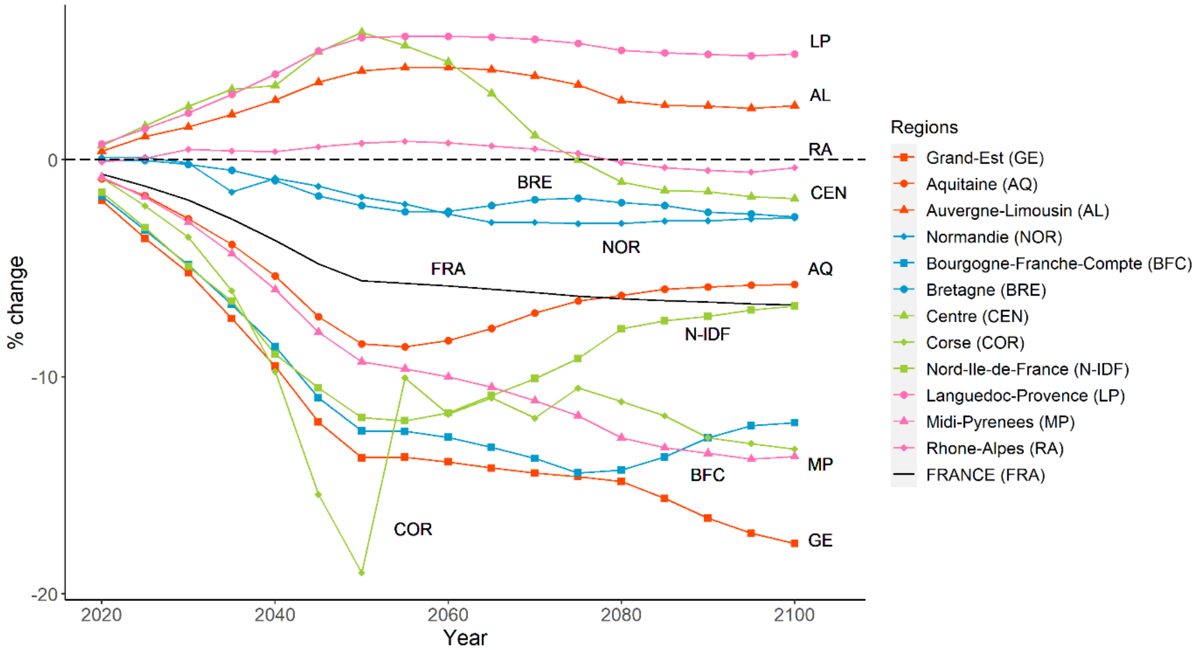


Figure 3.4 - Evolution of regional and national harvest levels in MAIN. Results are reported as percent changes against BAU over 5-year periods.

4.4. Management decisions

Despite representing more than half of all investments, there is a decrease in investments in coniferous high forests, going from 68.1% of investments in BAU to 56.7% in MAIN (Table 3.2). On the opposite, investments in mixed high forests increase from 8.5% to 11.5%, and investments in broadleaf forests with intermediate structure increase from 8.4% to 17.1%. Investments in other forest types remain relatively similar. In addition to changes in net investments, carbon rents lead to differences in the spatial distribution of forest cover types. Decomposing investment choices based on what was harvested, we observe that forest owners replant less often with the same species in LOW, MAIN and HIGH compared to BAU. In such cases, harvested area is allocated to a new forest type, leading to a change of forest cover. For example, in MAIN, 59.2% of management choices on average lead to such changes, against 40% in BAU. This increase is strongest for locations originally forested as coniferous high forests and coppices, while broadleaf forests with intermediate structure are less concerned. However, in absolute terms, coniferous high forests remain replanted identically after harvest in a majority of cases. As explained in the methods section, growth conditions in the model are heterogeneous across space. In LOW, MAIN and HIGH, land is more often attributed to forest

Table 3.2 - Harvest levels and post-harvesting management decisions, for each forest type. Changes are averaged over the simulation, and reported against BAU. Forest types are broadleaf high forest (1), mixed high forest (2), coniferous high forest (3), broadleaf forest with intermediate structure (4), mixed forest with intermediate structure (5) and broadleaf coppice (6).

Variable	Forest type	BAU	MAIN-F		LOW		MAIN		HIGH	
Harvest volume (Mm^3)	*All*	47.3	45.1	(-4.7%)	45.5	(-3.8%)	45	(-4.8%)	44.7	(-5.6%)
	1	10.6	9.7	(-8.7%)	9.9	(-6.8%)	9.7	(-8.7%)	9.5	(-10.2%)
	2	2.8	2.6	(-8%)	2.7	(-6.2%)	2.6	(-7.9%)	2.6	(-9.2%)
	3	20.2	19.9	(-1.2%)	19.9	(-1.4%)	19.8	(-1.7%)	19.8	(-1.8%)
	4	9.6	8.8	(-7.9%)	9	(-5.7%)	8.9	(-7.5%)	8.7	(-8.8%)
	5	2	2	(-0.7%)	2	(-0.3%)	2	(-0.3%)	2	(-0.3%)
	6	2.2	2.1	(-3.8%)	2.1	(-3.1%)	2.1	(-3.9%)	2.1	(-4.4%)
Investment share	*1*	9.1%	8.8%	(-0.3)	8.9%	(-0.3)	8.8%	(-0.3)	8.8%	(-0.3)
	2	8.5%	8.8%	(+0.4)	11.5%	(+3)	11.5%	(+3.1)	11.6%	(+3.1)
	3	68.3%	68.1%	(-0.1)	57.2%	(-11.1)	57%	(-11.3)	56.9%	(-11.4)
	4	8.4%	8.5%	(+0.1)	17%	(+8.6)	17.1%	(+8.8)	17.2%	(+8.8)
	5	4.9%	4.9%	(-0.1)	5%	(0.1)	5%	(+0.1)	5%	(0.1)
	6	0.9%	0.9%	(0)	0.5%	(-0.3)	0.5%	(-0.3)	0.5%	(-0.3)
Rotation times[21] (years)	*All*	130	129	(-0.7%)	210	(+61.3%)	210	(+61.6%)	212	(+63.1%)
	1	143	141	(-1.3%)	228	(+59.6%)	227	(+59.2%)	232	(+62.4%)
	2	111	111	(-0.7%)	2167	(+94.8%)	219	(+96.3%)	219	(+97.5%)
	3	96	96	(-0.1%)	231	(+139.9%)	232	(+141.4%)	234	(+142.7%)
	4	143	142	(-1%)	244	(+70%)	245	(+70.9%)	246	(+71.5%)
	5	119	119	(-0.4%)	171	(+43.3%)	172	(+44.1%)	172	(+44.3%)
	6	167	166	(-0.6%)	167	(0.3%)	165	(-0.9%)	169	(+1.2%)
Expected returns from timber[2] (€/ha)	*All*	89.4	92.1	(+3%)	8.3	(-90.7%)	7.5	(-91.7%)	6.7	(-92.5%)
	1	61.6	65.9	(+7.1%)	4.5	(-92.7%)	4.2	(-93.2%)	4	(-93.6%)
	2	86.4	91.1	(+5.5%)	7.7	(-91.1%)	6.8	(-92.1%)	6.2	(-92.9%)
	3	110.1	112.3	(+2%)	10.8	(-90.2%)	9.7	(-91.2%)	8.6	(-92.2%)
	4	59.8	63.9	(+6.8%)	3.5	(-94.2%)	3.2	(-94.7%)	3.1	(-94.9%)
	5	62.2	63.4	(+1.9%)	10.8	(-82.6%)	10	(-84%)	9.6	(-84.5%)
	6	5.8	6.6	(+14.4%)	0.7	(-88.3%)	0.5	(-91.8%)	0.3	(-95.7%)
Growth multiplier[22]	*All*	0.83	0.83	(-0.4%)	0.77	(-8.3%)	0.76	(-8.4%)	0.76	(-8.3%)
	1	0.79	0.78	(-1%)	0.63	(-19.3%)	0.63	(-19.6%)	0.64	(-19%)
	2	0.69	0.69	(-0.1%)	0.66	(-4.5%)	0.66	(-4.5%)	0.66	(-4.4%)
	3	0.89	0.89	(-0.2%)	0.85	(-4%)	0.85	(-4.1%)	0.85	(-4.1%)
	4	0.77	0.77	(-0.7%)	0.75	(-2.9%)	0.75	(-2.9%)	0.75	(-2.9%)
	5	0.72	0.72	(-0.3%)	0.55	(-23.2%)	0.55	(-23.2%)	0.55	(-23.1%)
	6	0.96	0.95	(-0.5%)	0.52	(-45.5%)	0.52	(-45.7%)	0.52	(-45.3%)
Cover change (% area harvested)	*All*	40%	39.8%	(-0.2)	58.9%	(+18.9)	59.2%	(+19.2)	59.3%	(+19.4)
	1	68%	68.5%	(+0.5)	84%	(+16)	84.3%	(+16.3)	84.5%	(+16.5)
	2	60.3%	58.7%	(-1.5)	78.6%	(+18.3)	78.6%	(+18.4)	78.7%	(+18.4)
	3	11.6%	12.4%	(+0.8)	35.4%	(+23.7)	35.9%	(+24.3)	36.2%	(+24.5)
	4	65.9%	65.7%	(-0.2)	73.5%	(+7.6)	73.7%	(+7.8)	74%	(+8.1)
	5	55.5%	55.8%	(+0.3)	81.5%	(+26)	81.7%	(+26.2)	81.9%	(+26.4)
	6	74.4%	73.89%	(-0.5)	98.2%	(+23.8)	98.3%	(+23.9)	98.3%	(+23.9)

[21] Rotation lengths and timber revenues are expected values at the moment the decision is made (after harvest).
[22] Growth potential is reported as the growth multipliers associated to newly established forests. A value of 1 indicates growth speed equal to the regional average, and values under 1 growth faster than the average. Negative changes indicate allocation of harvested areas to forest types with better growth potential than in BAU (c.f. Lobianco et al. (2015) for more details).

types with a better growth potential than in BAU (i.e., average growth multipliers decrease). This is consistent with carbon rents favouring species with better growth dynamics, leading to more to carbon storage. An analysis of pixel-level results shows that occurrences when investments are diverted from coniferous high forests towards other forest types are limited to locations where coniferous forests show lower growth potential than in locations where they are not displaced. At the same time, in these areas, the replacement forest type shows a higher growth potential than coniferous forests, and a higher growth potential compared to areas where it does not replace it (Table 3.3).

Table 3.3 – Average growth multipliers[23] in pixels attributed to coniferous high forests in BAU but to other forest types in MAIN.

	Locations where investment is diverted	Other locations	Overall
Coniferous high forest	0.90	0.82	0.89 (BAU) 0.85 (MAIN)
Replacement forest types	0.69	0.77	0.76 (BAU) 0.67 (MAIN)

In LOW, MAIN and HIGH, where management decisions follow Hartman's model, rotation times increase on average by 61-63% compared to BAU, reaching average values in the 150-250 years range (Table 3.2, Figure 3.5). The relative increase is strongest for coniferous high forests (+141%), and broadleaf forests with intermediate structure show the highest average rotation time at more than 240 years. In addition to increasing, rotation times also show higher variability in scenarios where decisions follow Hartman's model. Rotation times for coppices remain similar to those in BAU overall, but tend to decrease moderately in the long term. At the same time, expected revenues from timber decrease by 80-95%, which is consistent with delayed harvests and high carbon prices. On the opposite, in MAIN-F, where management decisions follow Faustmann's model, expected returns from timber are 2-14% higher than in BAU, which is consistent with higher timber prices and marginally shorter rotation times.

While average rotation times in MAIN reach values over 200 years in all regions except NOR, this increase is weakest in southeastern Mediterranean and mountainous regions (e.g. MP, LP, RA), where rotations were already long, while the highest relative increase is found in southwestern AQ, where rotation lengths were originally short (83 years in BAU). In all regions, 50% or more of harvested area undergoes a change of forest cover, except in AQ, where 62.5% is replanted with the same forest type. This region contains a large share of intensively managed pine plantations, which still represent 88% of replanted areas. Coniferous forests also keep representing a large majority of investments in other western regions (75-90% in BRE, NOR, CEN). Southeastern regions are more affected by increases in cover changes, and mixed or broadleaf forest types are more often favoured.

[23] Average growth multipliers across all pixels (regardless of whether the forest type is chosen in any scenario) is equal to 1. The "overall" column gives the average growth multipliers in all pixels where the forest type is chosen.

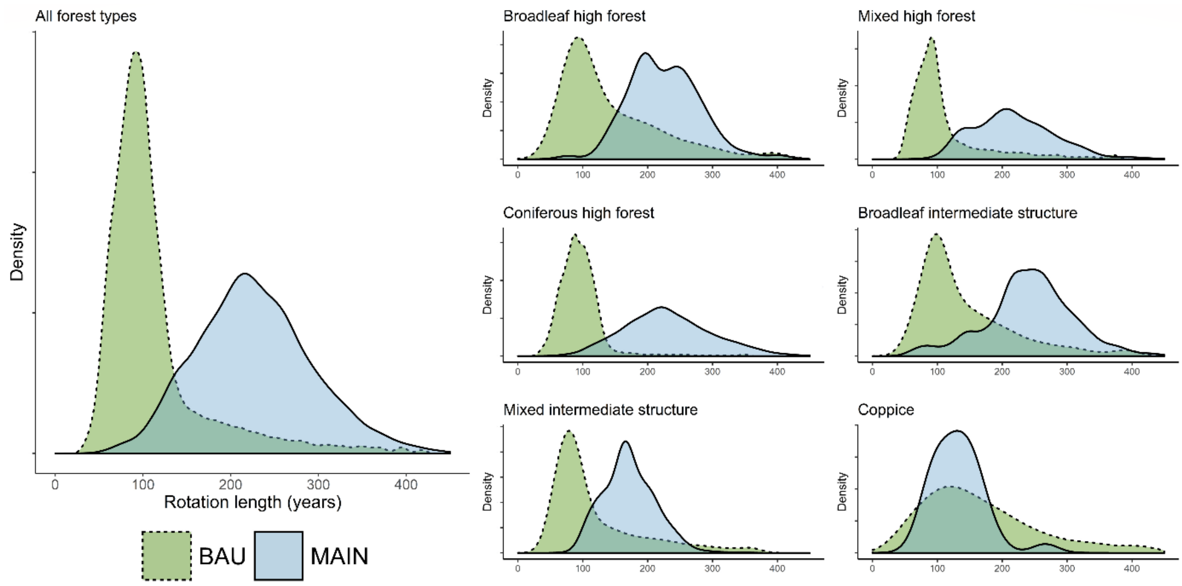


Figure 3.5 - Distribution of expected rotation lengths in MAIN and BAU. Values encompass all decisions taken throughout the simulations.

4.5. Long-term landscape implications

Over time, changes in harvesting and management decisions lead to changes in forest landscapes (Figure 3.6). At the national level, by 2100, France contains a lower area of pure coniferous forests in MAIN compared to BAU (-12.6%, -560.000 ha) but a higher share of mixed (+6.44%, 130.000 ha) and pure broadleaf (+5.6%, 430.000 ha) forests. The area of pure coniferous forests is lower in all regions except CEN, where it increases moderately (+7.3%, 27.500 ha). This decrease is particularly strong in AQ, RA and BFC, where it reaches 90.000 ha. The area of pure broadleaf forests increases in all regions but CEN. Relative increases are highest in western regions BRE (+12.5%) and AQ (+9.7%), and the highest absolute increases are found in eastern regions: BFC (84.000 ha), LP (83.000 ha) and GE (77.000 ha). The area of mixed forests undergoes contrasted evolutions across regions, with increases in southern and regions and decreases in northern regions, but absolute changes remain limited.

Regarding forest structure, at the national level, the area of high forest is moderately lower (-4%, 375.000 ha) and that of forests with intermediate structure higher (+10.2%, 388.000 ha), and general trends are consistent across regions. The area of coppices undergoes a limited decrease nationally (-1.9%, 13.000 ha), but displays regional variations. It increases e.g. in GE (+27%) and BFC (+37%), but decreases in e.g. LP (-9%) and CEN (-7.5%). In all regions, changes remain very low in absolute terms.

By 2100, medium and large trees represent a higher share of total timber volumes than in BAU. Timber volumes in the 35-75cm and more than 75cm diameters classes are 5.7% (100 Mm^3) and 6.4% (160 Mm^3) higher in MAIN than in BAU respectively, while they are only 1.8% higher (17 Mm^3) in the less than 35cm classes. This evolution is similar for most regions, and the trend is stronger in regions with high decreases in harvests, such as GE and BFC. Regions where harvest levels increase (CEN, LP, AL) undergo the opposite trend: volumes in the 35-75cm and more than 75cm diameters classes decrease (e.g., -3.1% and -5% in LP) due to being harvested and small trees represent a slightly higher share of total volumes (e.g., +1.2% in LP).

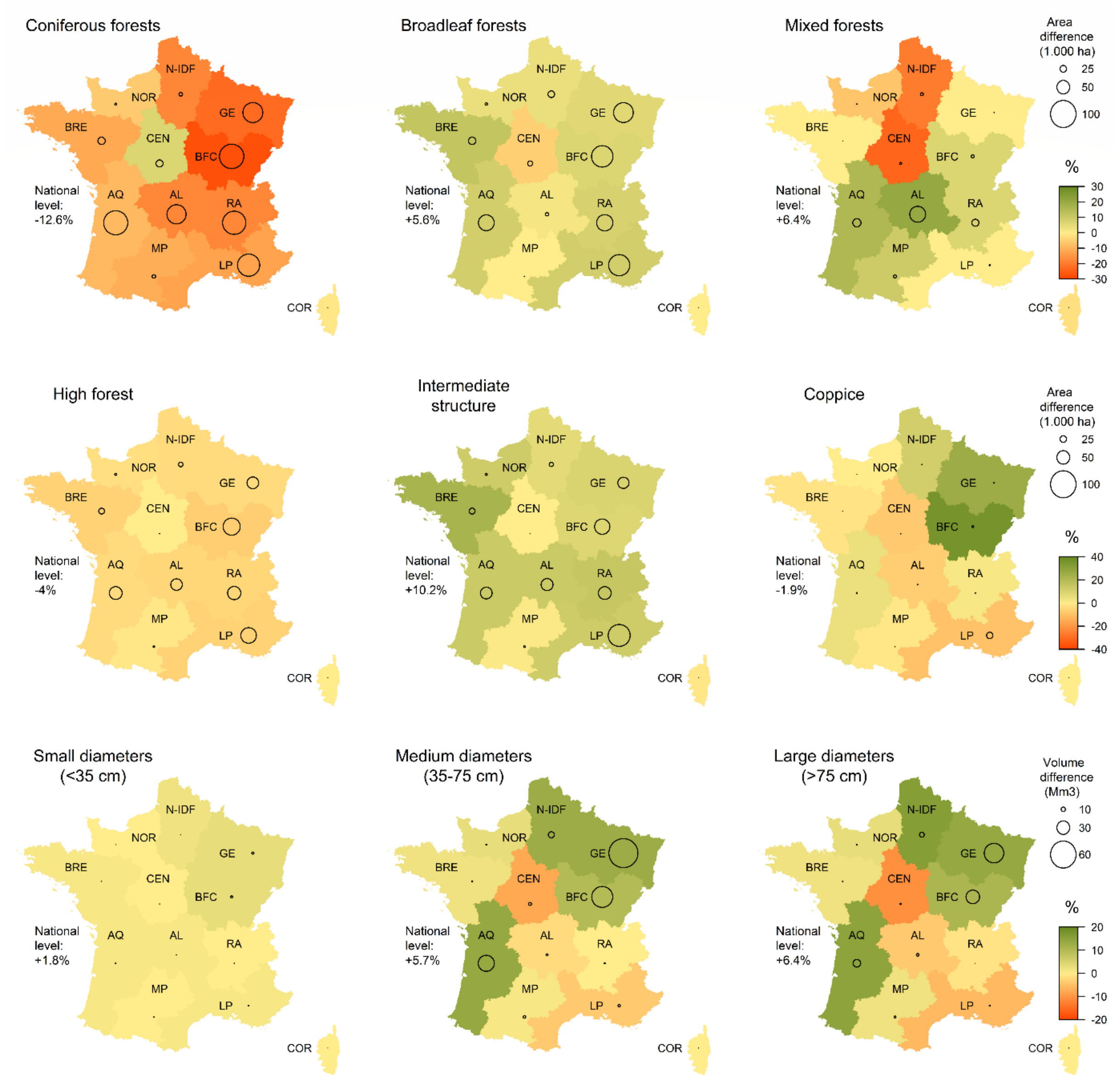


Figure 3.6 – Structure and composition of French forests in 2100 in MAIN compared with BAU. Circle size indicates absolute differences in areas or volumes and colours indicate relative differences.

5. Discussion

5.1. Climate and market implications of a sequestration incentive

Forest management for carbon sequestration alongside timber production was modelled by introducing Hartman's (1976) optimal rotation framework in a partial equilibrium model of the forest sector, implemented as carbon rents targeting *in situ* carbon stocks. This policy leads to higher carbon stocks compared to a business-as-usual scenario where forests are only managed for timber production. Carbon sequestered in products pools decreases due to lower harvest levels, but this loss is quickly offset by much higher gains in forest carbon. This is in line with Pohjola et al. (2018) who highlight that, even when carbon in long-lived products is subsidized, a carbon rent policy leads to decreases in products stocks. Increases in forest carbon stocks are sustained in time, showing that an actual incentive should be implemented on the long term. In particular, allowing management decisions to adapt in addition to harvest levels resulted in more carbon storage over the long term. This stands in contrast with results from Guo and Gong (2017), where carbon payments are most effective in the medium term, and Pohjola et al. (2018), where only low carbon prices yield sustained benefits. On the contrary, Sjolie *et al.* (2013) also report sustained benefits. Because the carbon rent acts as an opportunity cost to harvesting, harvests decrease and product prices increase as a consequence. The relative change in prices is higher than that of supply, and industrial wood is relatively more affected than other products due to its high carbon content-to-price ratio, while hardwood is more affected than softwood. Producer surplus increases while consumer surplus decreases, a trend described by others (Guo and Gong 2017b; Lecocq et al. 2011), which may render a sequestration policy complicated to implement. The decrease in supply also negatively affects timber exports, while more timber is imported as transformed products. Such an evolution may result in carbon leakage: international coordination in designing sequestration incentives may hence be necessary (Buongiorno and Zhu 2013).

5.2. Management practices, landscape impacts and non-climate benefits

Management practices show significant differences when the benefits associated to carbon storage are considered in forest owners' management decisions. Rotation times increase, which is consistent with previous applications of the optimal rotation framework (van Kooten and Johnston 2016). For instance, Gutrich and Howarth (2007) also use high carbon prices (up to 570$/t) consistent with ambitious climate objectives and report, for a set of temperate forests in the USA, rotations in the 200-450 years range, as well as decreases in timber revenues by 94-99%, which compare to our results. The relative economic profitability of management options is affected, and, even though it remains the most common choice overall, investments in coniferous forests decrease, while they increase for mixed and broadleaf forest types. We also highlighted different management responses from owners across regions, in particular when comparing western regions to southeastern Mediterranean regions.

Our model is spatial and takes into account heterogeneity in growth conditions. When carbon rents are implemented, land is more often attributed to forest types with the highest growth potential. In particular, results reveal that the displacement of coniferous forests by other forest types mostly concerns locations where coniferous species have lower than average growth potential. On the medium to long term, changes in investments affect sequestration dynamics, and carbon storage is higher in scenarios where investments are allowed to change. This effect increases over time as more area is replanted. Market impacts diverged only for softwood products: by the end of the simulation, supply was slightly lower and prices slightly higher when management adaptations were included, which is due to a long-term decrease in resource availability following less area being replanted with coniferous forests. The market module in FFSM is recursive, and decisions are made over the short term. As a result, agents have a limited ability to anticipate future availability, explaining the low and delayed effect.

Following changes in forest management, by the end of our simulations (2100), French forests contain a higher share of diverse forests in terms of both species composition and structure, and also comprise a larger share of medium to large-sized trees. Mature, multiple-species and multiple-age forests, despite lower growth rates at the individual tree level, often contain large amounts of carbon in biomass and soils, actively store carbon for a long time and may strongly contribute to climate change mitigation (Carey et al. 2001; Luyssaert et al. 2008). Such forests often boast high levels of biodiversity and provision of a wide array of ecosystem services (Brockerhoff et al. 2017; Coll et al. 2018; Gamfeldt et al. 2013; Van Der Plas et al. 2016). Diverse forests also exhibit lower levels of susceptibility and better resilience or resistance to some disturbances (Bauhus et al. 2017; Jactel et al. 2009). Sequestration incentives may then provide co-benefits in addition to climate change mitigation, in particular when they rely on practices in already mature forests, such as extended rotations or set-asides, which can be recognized in the generation of carbon offsets (Buotte et al. 2020; Freedman, Stinson, and Lacoul 2009; Simonet, Delacote, and Robert 2016).

5.3. A regional approach to sequestration incentives

Our results show large regional variations and confirm the importance of taking into account local conditions when designing sequestration incentives (Adams et al. 2011; Yousefpour et al. 2018). While harvests decrease overall, a few regions undergo increases in harvests and export their production to other regions. Increases in carbon stocks are highest in regions where harvests decrease the most, but additional carbon storage is highest in regions with faster growth dynamics. In these regions, relatively large amounts of carbon could be sequestered in the short term by postponing harvests or limiting them, e.g., by remunerating forest owners to set-aside part of their forestland. However, such a policy may prove difficult to justify in France, where average harvest levels are already well below annual increment, in particular in small-scale private forests, and would be at odds with current policies aiming at increasing timber production (Ministry of Agriculture 2016). A middle ground approach could be to enhance sequestration in public forests, which have an explicit objective to provide environmental amenities and are already well-exploited, while encouraging harvest increases in under-harvested private forests. On the other hand, our results also highlight that, over the long term, changes in investment and management decisions improve *in situ* sequestration. Incentives may then not only focus on extended rotations or set-asides, but also on wider improved forest management or forest conversion practices.

On the contrary, slow growth dynamics hampers additional carbon sequestration. For this reason, Mediterranean regions do not seem to be suitable for carbon sequestration programmes. Many of these already comprise large carbon inventories and are likely to be affected by increases in the severity and frequency of droughts, fires or pest outbreaks (Dupuy et al. 2020; Lindner et al. 2010). Policy measures in these regions may need to focus on mitigating the impacts of such disturbances and adapt management in order to ensure the permanence of existing carbon stocks. Tradeoffs between climate change mitigation, adaptation and economic activity are likely to be particularly strong in the southwestern Aquitaine region, characterised by a large industry based on fast-growing pine plantations and a high exposure to disturbances.

Despite fast growth dynamics, northwestern regions show moderate increases in carbon stocks due to their low forest cover and modest decreases in harvests throughout the simulations. Several assessments for the USA have shown the importance of considering land-use dynamics, and afforesting agricultural land can sequester a significant amount of carbon (Adams et al. 2011; Alig et al. 2010; Haim, White, and Alig 2015). While our model does not endogenously include land use dynamics, in these sparsely forested regions, afforestation could be a solution to leverage growth possibilities and sequester carbon on the medium to long-term.

5.4. Limitations of the study

Differences between results across simulation studies may come from different assumptions in modelling the forest sector. Some assume agents (e.g. forest owners, manufacturers) can anticipate future conditions, while others assume myopic agents. Models may or may not include endogenous forest management decisions, and describe forest resources with varying degrees of detail. In the FFSM, agents have limited foresight: harvests are short-term decisions while management choices are long-term decisions. Models also do not use the same calibration data, reflecting contrasting real-world situations, e.g. environmental conditions and timber industries are very different in France and Finland. All of these discrepancies can influence results (Latta, Sjolie, and Solberg 2013; Sjølie et al. 2015).

Forest-level studies using optimal rotation models derived from Hartman (1976) often use species-specific growth functions, and some use process-based growth simulators. We perform a large-scale assessment, and growth dynamics in our model are represented as diameter-class dynamics for groups of species. While we do consider spatial heterogeneity based on inventory data, our approach lacks the fine-grain details found in local assessments. Besides, our model uses a finite number of diameter classes and assumes that final cuts must take place. The literature suggests that, in some cases, it may be profitable never to harvest or move to continuous cover forestry (Assmuth and Tahvonen 2018; van Kooten and Johnston 2016). In its current form, our model cannot take these possibilities into account.

Similarly to previous studies (e.g. Guo and Gong, 2017; Adams et al., 2011; West et al., 2019), we chose to conservatively exclude carbon in harvested wood products from our analysis, as well as potential avoided emissions when these replace fossil-based alternatives. By doing so, we assume all carbon is released at harvest and likely underestimate the potential climate benefits of forest management practices. For a diverse range of forests, Hennigar et al. (2008) estimate that considering products pools may increase carbon storage by 5%, and by 6% if substitution effects are also maximised. However, when forest offsets are traded on markets, including the latter may yield to issues of double counting since they are usually also credited in the energy or construction sector (van Kooten and Johnston 2016). We chose to apply an additionality condition based on management without climate benefits, but references are usually political constructs, the choice of which can affect outcomes (Asante and Armstrong 2012; Lintunen, Laturi, and Uusivuori 2016; West et al. 2019). We used a range of high carbon prices consistent with France's climate objectives. There is evidence that sequestration costs in forests are lower (van Kooten, Laaksonen-Craig, and Wang 2009; Yousefpour et al. 2018), and actual prices on compliance and especially voluntary markets are much lower (Ecosystem Marketplace 2017): actual incentives likely would not require such high values. We also eschewed transaction and monitoring costs that occur when implementing actual projects. As a result, our simulation experiment is more akin to a thought experiment: results should be taken for their illustrative and explanatory qualities in highlighting trends and their underlying determinants, not understood as predictions.

Finally, we focused on the level of forest owners. As highlighted in at the beginning of this article, a sectoral approach to mitigation would likely also include incentives in downstream industries i.e. in the energy and construction sectors. For France, Roux et al. (2017) consider several mitigation scenarios and estimate that promoting wood utilization could yield mitigation outcomes of the same magnitude as keeping harvests at their current level, with the advantage of avoided emissions being permanent compared to *in situ* stocks, which are sensitive to e.g. fires and storms. Valade et al. (2018) compare several scenarios for increasing bioenergy production and report that such strategies would offset their carbon debt by 2040 at the earliest, showing that some could be mobilised over the long term. In the spirit of Baker's et al. (2019) global assessment, future research at the national level could focus on assessing trade-offs and complementarities between sequestration and substitution policies in the forest sector over the long term.

6. Conclusion

In order to investigate the implications of managing forests for timber production alongside carbon sequestration, we embedded a Hartman-based model of forest management in a forest sector market model. We projected developments in the French forest sector until the end of the century and assigned monetary values to carbon sequestered *in situ* accordingly to recent estimates of the shadow price of carbon in France. If forest owners were to manage forests to store carbon, forests could sequester an additional 490-550 $MtCO_2eq$ by 2100. Forestry practices would change markedly, with longer rotations, lower harvest levels, while species choice would also be altered. Due to interactions between local economic and environmental conditions, sequestration outcomes display an important spatial variability, both across and within regions. In the medium to long term, landscapes are affected by management adaptations, and, by the end of the century, French forests comprise a higher share of mature, mixed-species and mixed-structure forests, again with spatial discrepancies. Even though such an evolution may present benefits in terms of ecosystem services provision, sequestration incentives may prove complicated to implement due to their potential lack of adequacy with current policy aiming at increasing timber production. A spatially differentiated approach to sequestration incentives may be needed, with e.g. measures aiming at stabilising existing carbon stocks in Mediterranean regions prone to risks such as fires and pests, while afforestation, longer rotations and improved management could be more appropriate in other parts of the country. Our results highlight the importance of considering not only management-market feedbacks when designing incentives for sequestering carbon, but also local conditions, their heterogeneity across space, and the potential landscape implications of management changes.

References

ACR. 2018. "Improved Forest Management Methodology for Quantifying 70 GHG Removals and Emission Reductions through Increased Forest Carbon Sequestration on Non-Federal U.S. Forestlands."

Adams, Darius M, Ralph Alig, Greg Latta, and Eric M White. 2011. "Regional Impacts of a Program for Private Forest Carbon Offset Sales." Journal of Forestry 109(8): 444–61.

Alavalapati, Janaki R.R., and G. Andrew Stainback. 2005. "Effects of Carbon Markets on the Optimal Management of Slash Pine (Pinus Elliottii) Plantations." Southern Journal of Applied Forestry 29(1): 27–32.

Alig, Ralph, Greg Latta, Darius Adams, and Bruce McCarl. 2010. "Mitigating Greenhouse Gases: The Importance of Land Base Interactions between Forests, Agriculture, and Residential Development in the Face of Changes in Bioenergy and Carbon Prices." Forest Policy and Economics 12(1): 67–75.

Amacher, Gregory, Markku Ollikainen, and Erkki Koskela. 2010. Economics of Forest Resources. Cambridge, MA: The MIT Press.

Armington, Paul S. 1969. "A Theory of Demand for Products Distinguished by Place of Production" Staff Papers - International Monetary Fund 16(1): 159.

Asante, Patrick, and Glen W. Armstrong. 2012. "Optimal Forest Harvest Age Considering Carbon Sequestration in Multiple Carbon Pools: A Comparative Statics Analysis." Journal of Forest Economics 18(2): 145–56.

Assmuth, Aino, and Olli Tahvonen. 2018. "Optimal Carbon Storage in Even- and Uneven-Aged Forestry." Forest Policy and Economics 87(April 2017): 93–100.

Baker, J. S. et al. 2019. "Potential Complementarity between Forest Carbon Sequestration Incentives and Biomass Energy Expansion." Energy Policy 126: 391–401.

Bauhus, Jürgen et al. 2017. "Ecological Stability of Mixed-Species Forests." In Mixed-Species Forests: Ecology and Management, Berlin, Heidelberg: Springer Berlin Heidelberg, 337–82.

Birdsey, Richard et al. 2018. "Climate, Economic, and Environmental Impacts of Producing Wood for Bioenergy." Environmental Research Letters 13(5).

Brockerhoff, Eckehard G. et al. 2017. "Forest Biodiversity, Ecosystem Functioning and the Provision of Ecosystem Services." Biodiversity and Conservation 26(13): 3005–35.

Buongiorno, Joseph, Craig Johnston, and Shushuai Zhu. 2017. "An Assessment of Gains and Losses from International Trade in the Forest Sector." Forest Policy and Economics 80(December 2016): 209–17.

Buongiorno, Joseph, Ronald Raunikar, and Shushuai Zhu. 2011. "Consequences of Increasing Bioenergy Demand on Wood and Forests: An Application of the Global Forest Products Model." Journal of Forest Economics 17(2): 214–29.

Buongiorno, Joseph, and Shushuai Zhu. 2013. "Consequences of Carbon Offset Payments for the Global Forest Sector." Journal of Forest Economics 19(4): 384–401.

Buotte, Polly C., Beverly E. Law, William J. Ripple, and Logan T. Berner. 2020. "Carbon Sequestration and Biodiversity Co-Benefits of Preserving Forests in the Western United States." Ecological Applications 30(2): 1–11.

Canadell, Josep G, and Michael R Raupach. 2008. "Managing Forests for Climate Change Mitigation." Science 320: 1456–57.

Carey, Eileen V., Anna Sala, Robert Keane, and Ragan M. Callaway. 2001. "Are Old Forests Underestimated as Global Carbon Sinks?" Global Change Biology 7(4): 339–44.

Caurla, Sylvain, Philippe Delacote, Franck Lecocq, Julien Barthès, et al. 2013. "Combining an Inter-Sectoral Carbon Tax with Sectoral Mitigation Policies: Impacts on the French Forest Sector." Journal of Forest Economics 19(4): 450–61.

Caurla, Sylvain, Philippe Delacote, Franck Lecocq, and Ahmed Barkaoui. 2013. "Stimulating Fuelwood Consumption through Public Policies: An Assessment of Economic and Resource Impacts Based on the French Forest Sector Model." Energy Policy 63: 338–47.

Caurla, Sylvain, Franck Lecocq, Philippe Delacote, and Ahmed Barkaoui. 2010. The French Forest Sector Model: Version 1.0.

CITEPA, IGN, MTES, and MAA. 2019. The National Forestry Accounting Plan of France Including the Forest Reference Level (FRL) for the 2021- 2025 and 2026-2030 Periods.

CNPF. 2019. Label Bas-Carbone. Méthode Conversion de Taillis En Futaie Sur Souches.

Coll, Lluís et al. 2018. "Knowledge Gaps about Mixed Forests: What Do European Forest Managers Want to Know and What Answers Can Science Provide?" Forest Ecology and Management 407(June 2017): 106–15.

Dupuy, Jean-luc et al. 2020. "Climate Change Impact on Future Wildfire Danger and Activity in Southern Europe: A Review." Annals of Forest Science 77(2): 35.

Ecosystem Marketplace. 2017. 7 Fertile Ground State of Forest Carbon Finance 2017 Fertile Ground. Washington DC.

Englin, J., and J. M. Callaway. 1993. "Global Climate Change and Optimal Forest Management." Natural Resource Modeling 7(3): 191–202.

Englin, Jeffrey, and John M. Callaway. 1995. "Environmental Impacts of Sequestering Carbon through Forestation." Climatic Change 31(1): 67–78.

Eriksson, Ljusk Ola et al. 2012. "Climate Change Mitigation through Increased Wood Use in the European Construction Sector-towards an Integrated Modelling Framework." European Journal of Forest Research 131(1): 131–44.

Eriksson, Mathilda. 2015. "The Role of the Forest in an Integrated Assessment Model of the Climate and the Economy." Climate Change Economics 6(3).

European Parliament, and European Council. 2018. REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the Inclusion of Greenhouse Gas Emissions and Removals from Land Use, Land Use Change and Forestry in the 2030 Climate and Energy Framework, and Amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU. Brussels: European Parliament, European Council.

Favero, Alice, and Robert Mendelsohn. 2014. "Using Markets for Woody Biomass Energy to Sequester Carbon in Forests." Journal of the Association of Environmental and Resource Economists 1(1/2): 75–95.

Favero, Alice, Robert Mendelsohn, and Brent Sohngen. 2017. "Using Forests for Climate Mitigation: Sequester Carbon or Produce Woody Biomass?" Climatic Change 144(2): 195–206.

Freedman, Bill, Graham Stinson, and Paresh Lacoul. 2009. "Carbon Credits and the Conservation of Natural Areas." Environmental Reviews 17: 1–19.
Gabriella Cevallos, Julia Grimault, and Valentin Bellassen. 2019. Domestic Carbon Standards in Europe Overview and Perspectives. I4CE: Paris.
Galik, Christopher S., Robert C. Abt, Gregory Latta, and Tibor Vegh. 2015. "The Environmental and Economic Effects of Regional Bioenergy Policy in the Southeastern U.S." Energy Policy 85: 335–46.
Gamfeldt, Lars et al. 2013. "Higher Levels of Multiple Ecosystem Services Are Found in Forests with More Tree Species." Nature Communications 4(1): 1340
Gold Standard. 2017. Gold Standard Afforestation Reforestation (A/R) GHG Emissions Reduction & Sequestration Methodology. Version 1.
Gren, Ing Marie, and Abenezer Aklilu Zeleke. 2016. "Policy Design for Forest Carbon Sequestration: A Review of the Literature." Forest Policy and Economics 70: 128–36.
Guo, Jinggang, and Peichen Gong. 2017a. "The Potential and Cost of Increasing Forest Carbon Sequestration in Sweden." Journal of Forest Economics 29: 78–86.
Gutrich, John, and Richard B. Howarth. 2007a. "Carbon Sequestration and the Optimal Management of New Hampshire Timber Stands." Ecological Economics 62(3–4): 441–50.
Haim, David, Eric M White, and Ralph J Alig. 2015. "Agriculture Afforestation for Carbon Sequestration under Carbon Markets in the United States: Leakage Behavior from Regional Allowance Programs." Applied Economic Perspectives and Policy 38(1): 132–51.
Hartman, Richard. 1976. "The Harvesting Decision When A Standing Forest Has Value." Economic Inquiry XIV(March): 52–58.
Hennigar, Chris R., David A. MacLean, and Luke J. Amos-Binks. 2008. "A Novel Approach to Optimize Management Strategies for Carbon Stored in Both Forests and Wood Products." Forest Ecology and Management 256(4): 786–97.
Im, Eun Ho, Darius M Adams, and Gregory S Latta. 2007. "Potential Impacts of Carbon Taxes on Carbon Flux in Western Oregon Private Forests." Forest Policy and Economics 9(8): 1006–17.
IPCC. 2018. Ipcc - Sr15 Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways. Geneva.
Jactel, Hervé et al. 2009. "The Influences of Forest Stand Management on Biotic and Abiotic Risks of Damage." Annals of Forest Science 66(7).
JORF. 2018. Décret N° 2018-1043 Du 28 Novembre 2018 Créant Un Label « Bas-Carbone ». Paris.
Kim, Sei Jin, Justin S. Baker, Brent L. Sohngen, and Michael Shell. 2018. "Cumulative Global Forest Carbon Implications of Regional Bioenergy Expansion Policies." Resource and Energy Economics 53: 198–219.
Kollmuss, Anja et al. 2010. Handbook of Carbon Offset Programs: Trading Systems, Funds, Protocols and Standards Handbook of Carbon Offset Programs: Trading Systems, Funds, Protocols and Standards.
van Kooten, G. Cornelis, Clark S. Binkley, and Gregg Delcourt. 1995. "Effect of Carbon Taxes and Subsidies on Optimal Forest Rotation Age and Supply of Carbon Services." American Journal of Agricultural Economics 77(2): 365.
van Kooten, G. Cornelis, and Craig Johnston. 2016. "The Economics of Forest Carbon Offsets." Ssrn (April): 1–20.
van Kooten, G. Cornelis, Susanna Laaksonen-Craig, and Yichuan C Wang. 2009. "A Meta-Regression Analysis of Forest Carbon Offset Costs." Canadian Journal of Forest Research 39(11): 2153–67.
Latta, Gregory S., Hanne K. Sjolie, and Birger Solberg. 2013. "A Review of Recent Developments and Applications of Partial Equilibrium Models of the Forest Sector." Journal of Forest Economics 19(4): 350–60.
Latta, Gregory S, Darius M Adams, Kathleen P Bell, and Jeffrey D Kline. 2016. "Evaluating Land-Use and Private Forest Management Responses to a Potential Forest Carbon Offset Sales Program in Western Oregon (USA)."
Lauri, Pekka et al. 2014. "Woody Biomass Energy Potential in 2050." Energy Policy 66: 19–31. http://dx.doi.org/10.1016/j.enpol.2013.11.033.
Lecocq, Franck et al. 2011. "Paying for Forest Carbon or Stimulating Fuelwood Demand? Insights from the French Forest Sector Model." Journal of Forest Economics 17(2): 157–68.
Lindner, Marcus et al. 2010. "Climate Change Impacts, Adaptive Capacity, and Vulnerability of European Forest Ecosystems." Forest Ecology and Management 259(4): 698–709.
Lintunen, Jussi, Jani Laturi, and Jussi Uusivuori. 2016. "How Should a Forest Carbon Rent Policy Be Implemented?" Forest Policy and Economics 69: 31–39.
Lobianco, Antonello, Sylvain Caurla, Philippe Delacote, and Ahmed Barkaoui. 2016. "Carbon Mitigation Potential of the French Forest Sector under Threat of Combined Physical and Market Impacts Due to Climate Change." Journal of Forest Economics 23: 4–26.
Lobianco, Antonello, Philippe Delacote, Sylvain Caurla, and Ahmed Barkaoui. 2015. "The Importance of Introducing Spatial Heterogeneity in Bio-Economic Forest Models: Insights Gleaned from FFSM++." Ecological Modelling 309–310: 82–92.
———. 2016. "Accounting for Active Management and Risk Attitude in Forest Sector Models An Impact Study on French Forests." Environ Model Assess 21: 391–405.
Luyssaert, Sebastiaan et al. 2008. "Old-Growth Forests as Global Carbon Sinks." Nature 455(7210): 213–15.
McKechnie, Jon et al. 2011. "Forest Bioenergy or Forest Carbon? Assessing Trade-Offs in Greenhouse Gas Mitigation with Wood-Based Fuels." Environmental Science and Technology 45(2): 789–95.
Ministère de l'agriculture de l'agroalimentaire et de la forêt. 2016. Programme National de La Forêt et Du Bois 2016-2026.
Ministère de la transition ecologique et solidaire. 2017. Plan Climat. Paris.
Ministère de la Transition Ecologique et Solidaire. 2018. National Low Carbon Strategy Project: The Ecological and Inclusive Transition towards Carbon Neutrality. Paris.
Ministry of Agriculture, Agrifood and Forestry. 2016. THE NATIONAL FOREST AND WOOD PROGRAMME (PNFB). Paris.

Moiseyev, Alexander, Birger Solberg, and A. Maarit I. Kallio. 2013. "Wood Biomass Use for Energy in Europe under Different Assumptions of Coal, Gas and CO2 Emission Prices and Market Conditions." Journal of Forest Economics 19(4): 432–49.
Olschewski, Roland, and Pablo C. Benítez. 2010. "Optimizing Joint Production of Timber and Carbon Sequestration of Afforestation Projects." Journal of Forest Economics 16(1): 1–10.
Van Der Plas, Fons et al. 2016. "Jack-of-All-Trades Effects Drive Biodiversity-Ecosystem Multifunctionality Relationships in European Forests." Nature Communications 7: 1–11.
Pohjola, J., and L. Valsta. 2007. "Carbon Credits and Management of Scots Pine and Norway Spruce Stands in Finland." Forest Policy and Economics 9(7): 789–98.
Pohjola, Johanna, Jani Laturi, Jussi Lintunen, and Jussi Uusivuori. 2018. "Immediate and Long-Run Impacts of a Forest Carbon Policy—A Market-Level Assessment with Heterogeneous Forest Owners." Journal of Forest Economics 32: 94–105.
Quinet, Alain. 2019. The Value for Climate Action A Shadow Price of Carbon for Evaluation of Investments and Public Policies Report by the Commission Chaired By. Paris.
Riahi, Keywan et al. 2017. "The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview." Global Environmental Change 42: 153–68.
Riviere, Miguel, Sylvain Caurla, and Philippe Delacote. 2020. "Evolving Integrated Models From Narrower Economic Tools: The Example of Forest Sector Models." Environmental Modeling & Assessment In Press: 1–17.
Roux, Alice, Jean-François Dhôte, Claire Bastick, and Antoine Colin. 2017. Quel Rôle Pour Les Forêts et La Filière Forêt-Bois Françaises Dans l'atténuation Du Changement Climatique ? –
Samuelson, Paul A. 1952. "Spatial Price Equilibrium and Linear Programming." American Economic Review 42(3): 283–303.
Sauquet, Alexandre et al. 2011. "Estimating Armington Elasticities for Sawnwood and Application to the French Forest Sector Model." Resource and Energy Economics 33: 771–81.
Sedjo, Roger A., and Brent Sohngen. 2012. "Carbon Sequestration in Forests and Soils." Ssrn.
Simonet, Gabriela, Philippe Delacote, and Nicolas Robert. 2016. "On Managing Co-Benefits in REDD+ Projects." International Journal of Agricultural Resources, Governance and Ecology 12(2): 170–88.
Sjolie, H K, Greg S Latta, and Birger Solberg. 2013. "Potentials and Costs of Climate Change Mitigation in the Norwegian Forest Sector - Does Choice of Policy Matter?" Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere 43(6): 589–98.
Sjølie, Hanne K. et al. 2015. "An Assessment of Forest Sector Modeling Approaches: Conceptual Differences and Quantitative Comparison." Scandinavian Journal of Forest Research 30(1): 60–72.
Sohngen, Brent, and Sandra Brown. 2008. "Extending Timber Rotations: Carbon and Cost Implications." Climate Policy 8(5): 435–51.
Tavoni, Massimo, Brent Sohngen, and Valentina Bosetti. 2007. "Forestry and the Carbon Market Response to Stabilize Climate." Energy Policy 35(11): 5346–53.
UNFCCC. 2015. Paris Agreement. Paris: UN.
Valade, Aude et al. 2018. "Carbon Costs and Benefits of France's Biomass Energy Production Targets." Carbon Balance and Management 13(1).
Vass, Miriam Münnich, and Katarina Elofsson. 2016. "Is Forest Carbon Sequestration at the Expense of Bioenergy and Forest Products Cost-Efficient in EU Climate Policy to 2050?" Journal of Forest Economics 24: 82–105.
VCS. 2012. VM0003 Methodology for Improved Forest Management Through Extension of Rotation Age (IFM ERA). www.ecotrust.org (April 9, 2020).
———. 2015. "REDD+ Methodology Framework (REDD-MF)." VCS Methodology (v.1.5): 1–16.
———. 2017. 16 Requirements document Agriculture, Forestry and Other Land Use (AFOLU) Requirements.
Wernsdörfer, Holger et al. 2012. "Large-Scale Dynamics of a Heterogeneous Forest Resource Are Driven Jointly by Geographically Varying Growth Conditions, Tree Species Composition and Stand Structure." Annals of Forest Science 69(7): 829–44.
West, Thales A P, Chris Wilson, Maria Vrachioli, and Kelly A Grogan. 2019. "Carbon Payments for Extended Rotations in Forest Plantations : Con Fl Icting Insights from a Theoretical Model." Ecological Economics 163(February): 70–76.
Wunder, Sven. 2015. "Revisiting the Concept of Payments for Environmental Services." Ecological Economics 117: 234–43.
Yousefpour, Rasoul et al. 2018. "Realizing Mitigation Efficiency of European Commercial Forests by Climate Smart Forestry." Scientific Reports 8(1): 1–11.

Chapter 4

Forests under threat: assessing wildfire risk and climate-driven uncertainties with a large-scale forest model

Chapter 4

Forests under threat: assessing wildfire risk and climate-driven uncertainties in a large-scale forest model

1. Forest fires, climate change and implications for the forest sector

Forest fires, also referred to as wildfires, affects millions of hectares globally every year (Giglio, Randerson, and Van Der Werf 2013). While they are an inherent part of ecological processes and enable among others landscape opening and stand replacement (Pausas and Keeley 2019), they can also have adverse effects (Gill, Stephens, and Cary 2013). These include damages to environmental assets such as animals, plants or regulation services (Hood et al. 2018; Averett 2016; Verma and Jayakumar 2012), and damages to socio-economic assets such housing, public infrastructure or human health (Westerling and Bryant 2007; Kochi et al. 2010). Though these impacts, wildfires indirectly disturb activities such as tourism, forestry and agriculture while also requiring funding for suppression and prevention (Butry et al. 2001; Molina Martínez et al. 2011; Englin, Loomis, and González-Cabán 2001; Handmer and Betts 2013; Jin et al. 2015). They also have a feedback on the climate system by, among others, releasing carbon into the atmosphere, affecting vegetation cover and weather patterns (Liu, Goodrick, and Heilman 2014).

Most fires in Europe occur around the Mediterranean (San-Miguel-Ayanz et al. 2019), a region characterized by warm summers with frequent droughts and relatively high winter precipitations that enable fuel build-up. In France, fire activity is largely located in the south-eastern corner of the country[24], with over 60% of national burned areas in the 2010-2019 period[25]. Fires arise from the encounter of several factors: fuel conditions, climate-weather conditions and ignition agents (Flannigan et al. 2009). In southern Europe, fires are mostly caused by people close to activity clusters, either voluntarily or accidentally, while natural, lightning-caused fires are rarer and generally occur in remote locations (Ganteaume et al. 2013). In the past century, rural exodus has led to land abandonment, landscape homogenisation and colonisation of pasture by forests. Rapid urban expansion, extension of road networks and large-scale tourism have also transformed the landscape (Moreira et al. 2011). As a result, burned areas have increased up to the 1990s but, following improvements in fire prevention, monitoring and suppression, they have subsequently decreased (J. Ruffault, Mouillot, and Peters 2015; Fréjaville and Curt 2015; 2017). Even though human activity and policy are strong drivers of fire activity, climate plays a significant role. Over the last decades, weather conditions prone to fire activity[26] have become more frequent (Fréjaville and Curt 2015; Julien Ruffault et al. 2013; Jolly et al. 2015), a change which can be attributed to

[24] The region is known as the Promethée area following the establishment of the eponymous database of fire activity.
[25] As per the national BDIFF database, available at https://bdiff.agriculture.gouv.fr/.
[26] Conditions favorable to fire ignition and spread include high air temperatures, low relative humidity, high wind speed, high fuel load, low fuel moisture and fuel continuity across the landscape (Flannigan et al. 2009).

anthropogenic climate change (Barbero et al. 2020). For the decades to come, forecasts predict increased summer temperatures and reduced precipitations, leading to more frequent and intense droughts and a gradual desertification of the area (Giorgi and Lionello 2008). As a result, fire danger is expected to increase (Kovats et al. 2014), eventually emerging from its historical range (Abatzoglou, Williams, and Barbero 2019; Fargeon et al. 2020). Forecasts reviewed by Dupuy et al. (2020) report a projected increase in fire danger by 2-4% per decade (7% in France), a lengthening of the fire season by 3-4 days and an increase in its severity by 3-7% per decade. Uncertainties regarding burned areas are higher, but the literature generally forecasts increases ranging from a few percentage points up to 25% per decade. In France, fuel load and continuity are not limiting factors and burned areas are expected to increase significantly and reach new areas, expanding northwards and westwards. (Chatry 2010; Fargeon 2019).

When it comes to wildfires, the forest sector is in the frontline. Its primary resource, timber, is directly affected, potentially jeopardizing economic activity downstream but also the sector's climate mitigation potential (Le Page et al. 2013; Seidl et al. 2014). In a context of climate change characterized by a high degree of uncertainty, assessments are needed to better comprehend the implications of changing fire regimes on the forest sector. Due to the time scales involved, prospective analysis in the forest sector is often carried out with Forest Sector Models (FSM), i.e. large-scale simulation tools that take into account retroactions between timber industries, forest management and forest resources (Latta, Sjolie, and Solberg 2013). While FSM are commonly used for policy analysis and projection, applications to natural disturbances, including wildfires, remain scarce (Riviere, Caurla, and Delacote 2020). Most of the time, these eschew modelling disturbances and their effects, instead focusing on the costs and allocation of prevention (e.g. Prestemon, Abt, and Huggett 2008; Adams and Latta 2005) or recovery measures (e.g. Prestemon et al. 2013; Caurla, Garcia, and Niedzwiedz 2015). When they are modelled, disturbances and their impacts are represented through exogenous parameters estimated from empirical data or the literature, and as deterministic processes. Such approaches have for example been applied to wildfires (Sohngen and Haynes 1997) and pathogens (Petucco, Lobianco, and Caurla 2019).

These gaps can be explained by two factors. First, many FSM use a simplified matrix-based representation of forest resources, some only consider total timber inventories, and data is often aggregated over large spatial scales. Second, FSMs use combinations of rules and equations that only allow deterministic simulations. Wildfires are localised and highly stochastic events and their behaviour and effects depend on local environmental conditions: FSM seem a priori ill equipped to model them. While not a FSM in the strict sense, EFISCEN[27] is a large-scale model that shares many similarities with FSMs. Disturbances, including wildfires, have been addressed in several model extensions, some of which include a stochastic component (Schelhaas et al. 2002; Seidl et al. 2014; 2009). These generally leverage the model's stronger focus on representing biological dynamics, corroborating our hypotheses, even though a high level of spatial aggregation remains. On the other hand, wildfire risk has been a more important focus in the forest economics literature at the local or stand scale, which uses optimal rotation models derived from the seminal works of Faustmann (1849) and Reed (1984) to study risks for forest owners and management adaptations (e.g. Couture and Reynaud 2011). From a more general perspective, even though a

[27] EFISCEN does not include an economic component and focuses on biological dynamics and the evolution of forest resources on large scales.

few contributions have started to address the issue for model parameters using Monte-Carlo simulation (Kallio 2010; Buongiorno and Johnston 2018), the question of risk has proven problematic in FSM modelling due to high computational requirements, and uncertainty is most often addressed only through scenario and sensitivity analyses[28] (Chudy, Sjølie, and Solberg 2016).

The work presented in this chapter fills a gap in the literature by performing a long-term assessment of wildfire risk and climate-induced uncertainties at the scale of the forest sector. Our first objective is to better understand the propagation of uncertainties from the climate system to the forest sector and to highlight implications for model forecasts. Our second objective is to assess forest sector impacts of changing fire regimes by the end of the century, focusing on forest resources, carbon stocks and management decisions by forest owners. In order to take into account the local determinants of wildfire risk while retaining some degree of genericity, we focus on the regional scale and take the example of Southern France, where wildfire activity is expected to strongly increase in the decades to come. To reach our objectives, we establish a soft-coupling[29] between the FFSM and a probabilistic model of fire activity, and we develop a fire effects module based on empirical evidence from the literature and expert advice. We simulate fire activity for a range of climate scenarios driven by the choice of radiative forcing levels and climate models, and perform multiple replications of each scenario. We subsequently adapt uncertainty-partitioning methods from the climate science literature to quantify and disentangle uncertainties in model projections.

This chapter is organised as follows. In section 2, we give an overview of concepts underlying fire risk, present different modelling paradigms and justify our modelling choices. In section 3, we introduce the model coupling, we describe our scenarios and explain the process for analysing data and assessing uncertainty. Results are presented in two sections. In section 4, we analyse the impacts of changing fire regimes on the forest sector while, in section 5, we focus on the propagation of different sources of uncertainties in model projections. In section 6, we discuss some of the limitations of our approach and explore ways to improve fire modelling for more realistic scenario building. In particular, we discuss the potential to introduce spatially-explicit land-use and socio-economic predictors into the fire activity model to reduce spatial bias, which we explore using Boosted Regression Trees, a machine-learning algorithm. Finally, we discuss the general implications of our work in section 7.

2. Methodological considerations in introducing wildfire risk in forest sector models

2.1. The components of fire risk

Risk analysis is concerned with the study of uncertain events, stochastic in space or time, in particular those with low probabilities of occurrence but high consequences. Consequently, fire risk analysis is concerned with how often and where fires burn, and what their effects are (Miller and Ager 2013; Finney 2005). Even though terminology is sometimes disputed (Hardy

[28] In scenario analysis, the operator manually changes values for exogenous parameters, which together make up the "scenario", i.e. a particular narrative about the future. In sensitivity analyses, they change values for model parameters and initial conditions.

[29] By soft coupling, we understand a multi-model framework where the outputs of one model are used as inputs for the next model. Such frameworks are increasingly used in FSM research as a way of overcoming model limitations, including for the FFSM (Caurla et al. 2018; Beaussier 2020; Delacote et al., in print.).

2005), *fire risk* is generally considered to encompass 3 components, also referred to as the fire risk triangle (Finney 2005; Miller and Ager 2013; Brown 2001; Scott 2006; Xi et al. 2019; Preisler and Ager 2013).

1. *Likelihood* (Figure 4.1) refers to the probability of a fire happening. It is related to the more general concept of *hazard*, i.e. "the possible, future occurrence of natural or human-induced physical events that may have adverse effects on vulnerable and exposed elements" (Cardona et al. 2012). Likelihood can be estimated either as an *occurrence probability* (or ignition probability), i.e. the probability that a fire will start at a particular point in space and time, or as a *burn probability*, i.e. the probability that fire will encounter a particular place over a time period. Burn probability is particularly relevant at the landscape scale and below for fuel treatment planning, while occurrence probability is more relevant at larger scales, particularly in regions with smaller fires and a strong human presence, where it can be used as a surrogate for fire risk (Preisler and Ager 2013).

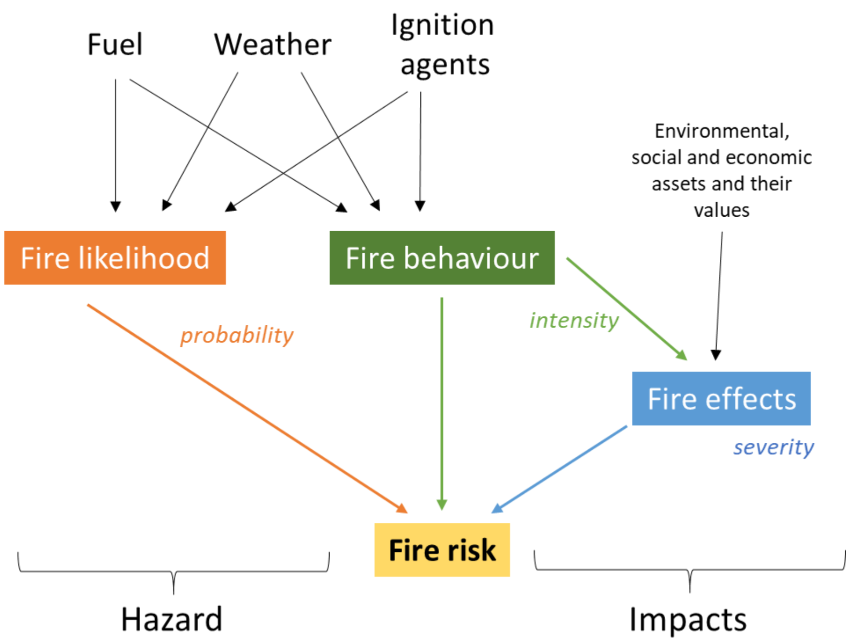


Figure 4.1 - The components of fire risk, adapted from Miller and Ager (2013), Xi et al. (2019) and Scott (2006).

2. *Behaviour* refers to the way a given fire event reacts to fuel, topographic and weather conditions. It is commonly quantified with variables such as fire intensity, flame length, rate of spread or scorch height. Fire intensity (kW/m) refers, in the stricter sense, to "a measure of energy output and is a function of the fuel burning and fire weather conditions", but is sometimes also used as a synonym to behaviour (Flannigan et al. 2009; Miller and Ager 2013).

3. *Effects* refer to "the change in ecological, social and economic values" as a result of fire behaviour (Miller and Ager 2013). Effects can be positive or negative and are further separated into first-order effects, e.g. tree mortality due to crown and cambial damage, and second-order effects, e.g. increased erosion due to decreased tree cover (Vaillant, Kolden, and Smith 2016). They are usually quantified in biophysical units (e.g. tons of lost carbon) and economic valuation techniques can be used to attribute a value in monetary

units. The term *fire severity* is encountered with various meanings across the literature, but usually relates to the order of magnitude of fire effects, e.g. depth of burn (Flannigan et al. 2009).

While the three components of fire risk are generally agreed upon, many subcomponents have been assessed and modelled with a variety of approaches (Figure 4.2).

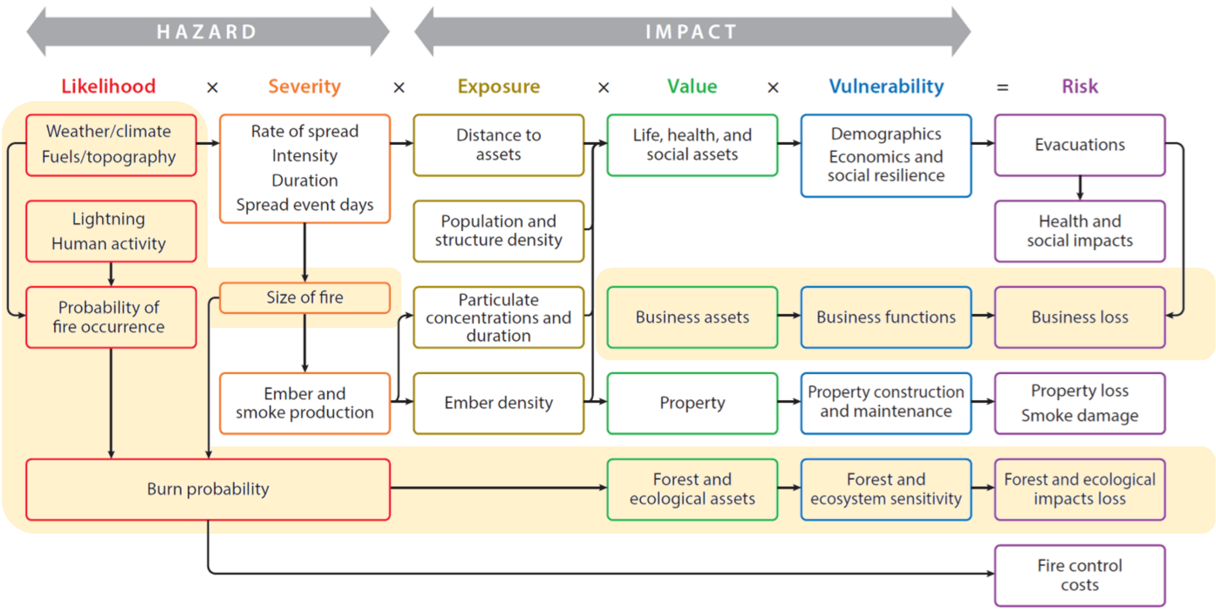


Figure 4.2 – The components of fire risk from Xi et al. (2019), and aspects treated with our model coupling (pale yellow).

2.2. Fire activity modelling

A broad distinction is often made between empirical models, which establish relationships between observations of fire activity and predictor variables, and process-based, mechanistic and physical models, which directly represent the processes underlying fire activity (Taylor et al. 2013; Dupuy et al. 2020; Preisler and Ager 2013). These methods differ regarding data requirements, complexity and the metrics they model. Given the geographical scale at which the FFSM operates, we considered approaches at the landscape scale and above (Figure 4.3).

- *Fire danger index projection* maps future fire hazard by computing values for a fire danger metric, most commonly the Fire Weather Index[30] (FWI) based on projections of e.g. weather and land-use variables (e.g. Fargeon et al. 2020). This method does not enable an explicit representation of fire activity and was not used.

- *Process-based models* synthesize knowledge from various fields (e.g. fire ecology, tree physiology, climatology) to explicitly simulate fire ignition, spread and effects, from the tree to the landscape scales. Widely used simple models include Rothermel's (1972) fire spread model and Van Wagner's (1977) crown fire model. Recent improvements include algorithms able to simulate large amounts of individual fires over a small region to

[30] The FWI was developed by the Canadian Forest Service (Van Wagner 1987b) for operational purposes. It comprises several sub-indices that indicate the effect of weather on fuel moisture content and fire behaviour, calculated from weather data (wind speed, air temperature, relative humidity and precipitations).

estimate burn probabilities (Preisler and Ager 2013; Miller and Ager 2013; Taylor et al. 2013). While these methods can explicitly represent most components of fire risk, they often have high computational requirements, need data at very fine scales (e.g. hourly to daily weather conditions, understory structure, fuel moisture) and were therefore incompatible with the FFSM.

- *Dynamic Global (and regional) Vegetation Models (DGVMs)* are large-scale simulators of terrestrial ecosystems, their dynamics (e.g. net primary productivity) and interactions with the climate system. Several DGVMs have been "fire-enabled", i.e. they integrate a sub-model for fire activity based on combinations of empirical, process-based and rule-based methods (Hantson et al. 2016). These models are still under development, are built for continental-global[31] scales and comprise information redundant with the FFSM, which raises issues concerning model compatibility.

- *Empirical models* establish a relationship between a fire activity metric (e.g. fire number) and predictor variables (e.g. weather variables) using empirical observations, and extrapolate predictions into the future. Most use statistical methods (e.g. generalised linear models) but machine-learning algorithms (e.g. neural networks) are increasingly used and perform well (Costafreda-Aumedes, Comas, and Vega-Garcia 2017). *Correlative approaches* establish a direct relationship between the activity metric and predictors and usually aggregate data spatially or temporally. *Probabilistic approaches* represent individual fires as spatio-temporal point processes on a grid map and model ignition probability and sometimes fire size.

Empirical approaches have been developed at the regional scale (e.g. Carvalho et al. 2008) or on 1-10km grid cells (e.g. Ager et al. 2014; Westerling et al. 2011), have moderate data and computation time requirements and, once estimated, can be easily used for simulation. While they cannot explicitly model fire behaviour in a bottom-up manner, they represent fire activity through emergent properties such as fire count and fire size, which are well-adapted to our study scale (Xi et al. 2019; Hantson et al. 2016; Preisler and Ager 2013; Miller and Ager 2013; Taylor et al. 2013). Besides, probabilistic models take into account stochasticity in the fire process, which constitutes an interesting opportunity to study uncertainties in projections. We therefore chose to integrate fire activity in the FFSM using an empirical, probabilistic approach.

2.3. Fire effects modelling

Like fire activity models, fire effects models can be classified into two broad categories. On the one hand, empirical models use logistic regression to estimate tree mortality in relation to tree traits (e.g. bark thickness, diameter) and fire intensity or severity metrics (e.g. char height), using data from post-fire field measurements. These models are often implemented in larger fire effects simulation software, where, owing to their being available only for a few species, they are either extrapolated or used in a generic, non-species-specific form (Hood et al. 2007; 2018; Woolley et al. 2012; Fernandes et al. 2008; Ryan and Amman 1994). On the other hand, process-based and, more recently, physics-based models seek to explicitly model damage processes. These models have high computational and data requirements and enable

[31] Typical grid cell sizes for a DGVM are 50-100km.

computing metrics such as fireline intensity, flame residence time and damage to stem tissues (Pimont et al. 2016; O'Brien et al. 2018).

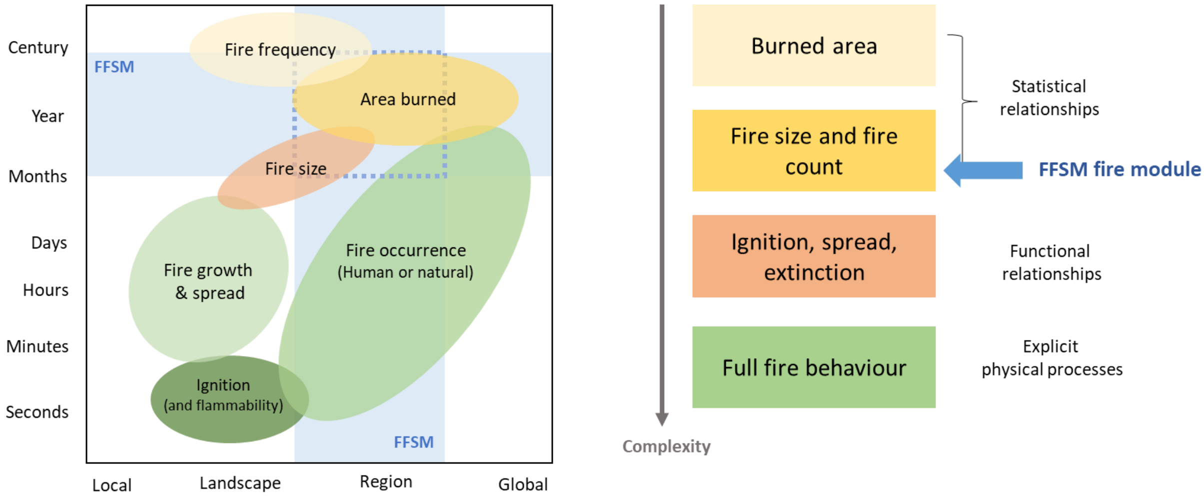


Figure 4.3 - Narrowing the choice: (left) fire risk components and their spatial and temporal scales of relevance, with the FFSM scale range in light blue, adapted from Taylor et al. (2013); (right) levels of complexity in representing fires in a vegetation model, adapted from Hantson et al. (2016).

These methods have been introduced in larger simulation frameworks such as fire-enabled DGVMs (Hantson et al. 2016). At one end of the spectrum, low-complexity DGVM fire modules model fire effects as a time-invariant loss of biomass. At the other end of the spectrum, high-complexity modules such as SPITFIRE (Thonicke et al. 2010) directly apply a suite of process-based models, often making simplifying assumptions[32]. A middle-of-the-road approach is found in "intermediate complexity" DGVMs, where burned areas determined with process-based approaches are distributed among plant functional types (PFTs) proportionately to their cover shares, and PFT-specific mortality coefficients are specified (Li, Zeng, and Levis 2012; Arora and Boer 2005; Thonicke et al. 2001; Venevsky et al. 2019; Kloster et al. 2010). A related approach based on a proportional attribution of damages and the use of "susceptibility" categories was developed for the large-scale forest simulator EFISCEN (Schelhaas et al. 2002).

Resource modelling in the FFSM shares characteristics and limitations with large-scale vegetation models, but benefits from more detailed information regarding forest structure and composition. We develop a simple fire effects module based on (1) the intermediate-complexity DGVM approach, and we use (2) the empirical literature on post-fire tree mortality in Mediterranean Europe to adapt it to our specific case.

3. Methods: fire modelling in the FFSM, scenario building and uncertainty partitioning

3.1. A probabilistic model of fire activity for Mediterranean France

We use a probabilistic model of fire activity developed for southern France (Pimont et al. in print) where fires are modelled as a spatial-temporal marked point process. The model comprises two sub-models: a fire occurrence model (for the points) and a fire size model (for

[32] DGVMs do not usually discriminate tree species nor diameter classes, but use Plant Functional Types (PFTs, e.g. deciduous broadleaves temperate species) where trees are represented as representative individuals.

the marks). They both function at the level of 8km-wide pixels from the SAFRAN grid (Moigne 2002) and respectively seek to model, from a set of predictors and at the daily scale, the number of fires larger than 1ha and their sizes, i.e. burned areas (BA).

The first main predictor is the Fire Weather Index (FWI), an indicator of fire danger developed by the Canadian Forest Service (Van Wagner 1987a) computed from weather variables (wind speed, precipitation, air temperature and relative humidity) and widely used to assess fire danger (Dupuy et al. 2020). Weather data is retrieved from the SAFRAN reanalysis (Vidal et al. 2010) and FWI is computed following the procedure in Bedia et al. (2014) using the "cffdrs" R package (Wang et al. 2017). The second main predictor is wildland area (WA). WA is obtained from the Corine Landcover (CLC)[33] database by computing, for each pixel, land area belonging to land-use classes "forest" and "shrubland" (CLC classes 31 "forests", 322 "moors and heathland", 323 "sclerophyllous vegetation" and 324 "transitional woodland/shrub") in GIS software (QGIS.org 2020). CLC data is available for years 1990, 2000, 2006, 2012 and 2018: a linear interpolation was carried out between these years. Fire observations are retrieved from the PROMETHEE database, which covers the Mediterranean region of France (Figure 4.4, Appendix D.1), with observations spanning the 1995-2018 period[34]. To limit uncertainty related to the registration of small fires, only fires larger than 1ha are considered. We also only considered summer fires (weeks 22 to 44) which represent the vast majority of BA in the PROMETHEE area. The model is estimated using data from the 1995-2015 period, the remaining data is used for evaluation[35].

The occurrence sub-model models fire count in a pixel-day (or voxel) as a Poisson random variable. In addition to FWI and WA, it incorporates two effects to account for unexplained variability: a temporal, weekly effect to account for fire seasonality, and a spatial, pixel-level effect to account for spatial variability, both specified using the Stochastic Partial Differential Equation approach. WA is also added as an offset to account for the fact that fires cannot occur in non-wildland areas. The full occurrence sub-model computes the number of fires N in a pixel px a given day d as:

$$[8] \quad N_{px,d} \sim WA * f(WA_{px}) * g(FWI_{px,d}) * h(WK_d) * i(X, Y_{px})$$

where WK is the week number and X and Y the pixel's geographical coordinates, while letters $\{f, g, h, i\}$ refer to the non-linear response functions.

The fire size sub-model predicts fire sizes for fires larger than 1ha using FWI and WA as the sole predictors. A piecewise distribution of fire sizes is fitted with 10ha, 100ha and 1000ha as the thresholds, using power-law distributions for the first 3 segments and a generalized Pareto distribution for the last segment[36] (i.e. fires larger than 1000ha). For each threshold, exceedance probabilities (i.e. the probability that a fire is larger than the threshold) are estimated with a logistic regression model:

[33] https://land.copernicus.eu/pan-european/corine-land-cover
[34] https://www.promethee.com/
[35] WA was computed by Miguel Riviere. Co-authors at INRAE URFM performed otherwise built the fire activity model (Pimont et al. in print).
[36] The generalized Pareto distribution was chosen because it enables setting a finite upper limit to fire sizes.

$$[9] \quad log\left(\frac{p_{u,i}}{1-p_{u,i}}\right) = \beta_u^0 + j(FWI_i) + k_u(WA_i)$$

where p is the exceedance probability, $u = \{10{,}100{,}1000\}$ refers to size thresholds, $i = \{px, d\}$ to pixel-days, functions $\{j, k\}$ denote non-linear responses to predictors and β^0 is the model's intercept. The resulting model enables the generation of fire sizes in a hierarchical manner: exceedance probabilities are used to simulate the interval in which a given fire falls, then, the associated fire size distribution enables determining BA.

Both sub-models are estimated in a Bayesian framework using the nested Laplace approximation (INLA, Rue, Martino, and Chopin, 2009) implemented in the R software (Lindgren and Rue 2015), which enables, among others, fitting models to large datasets and estimating non-linear relationships between predictors and the dependent variables. Detailed information on model building, estimation and validation can be found in (Pimont et al. in print; Fargeon 2019), we also provide summary information in Appendix D.2.

3.2. Soft-coupling with the FFSM

In the soft-coupling between the fire activity model and the FFSM, the former is used to generate fire counts and sizes at the scale of pixel-days, which we call *fire histories*, for the period 2020-2100. Fire histories then serve as inputs for the FFSM, where they are used to model an additional, fire-induced mortality (Figure 4.4).

3.2.1. Study area

While the fire activity model was originally developed for the PROMETHEE area, the area subject to moderate to high fire risk is expected to expand in the decades to come, reaching in particular the Aquitaine region with potentially significant impacts on the pine wood industry (Dupuy et al. 2020; Chatry 2010). Fire observations are available for most other French regions from the BDIFF database, but data quality and quantity is heterogeneous and does not allow for model estimation. Fargeon (2019) showed the good predictive performance of the model for annual fire numbers in most *départements* in the southern half of the country (also, cf. Appendix D.2). We extrapolate predictions from the model calibrated with PROMETHEE data to an area roughly corresponding to the southern half of the country, covering 5 FFSM regions, and therefore loose the pixel spatial effect (function i in equation 8). In section 5, we discuss avenues for decreasing spatial bias in the model and therefore improving extrapolated predictions. To ensure compatibility between the models, the FFSM grid was displaced to align on the SAFRAN grid, and corresponding initial conditions for forest resources were computed from CLC and National Forest Inventory data following Lobianco et al. (2015).

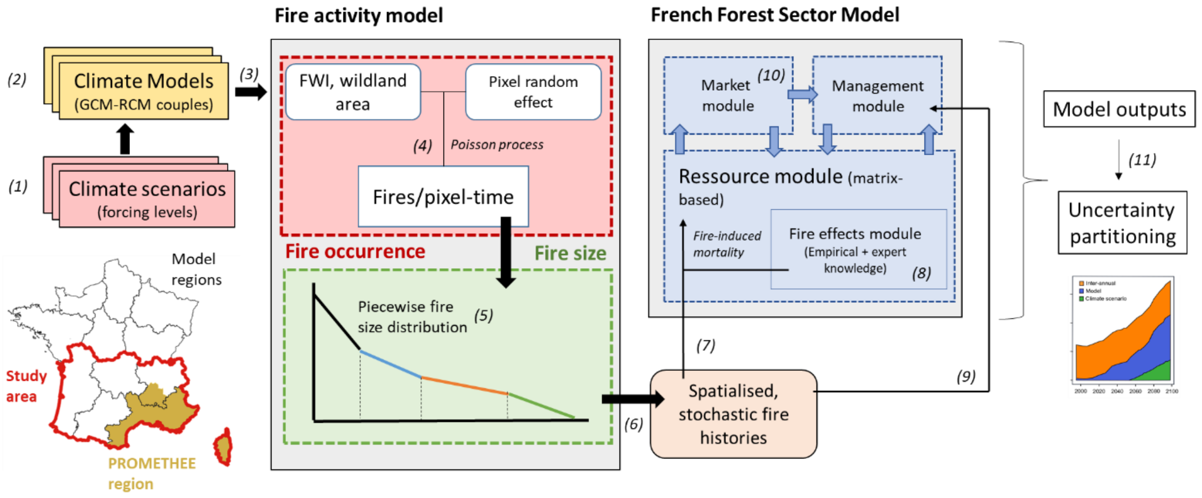


Figure 4.4 – Illustration of the coupling framework. From left to right: simulation data from several GCM-RCM couples (2) under various levels of radiative forcing (1) are used to drive a model of fire activity (3). Individual fires larger than 1ha are simulated on a 8km pixel grid in a hierarchical process where fire occurrence (4), fire size classes and burned areas (5) are computed sequentially, and several stochastic replications are carried out (6), forming fire histories. Burned areas are cumulated annually and applied to the French Forest Sector Model proportionately to forest area cover in pixels (7). Fire-induced mortality is computed using regional, species specific and diameter-class specific mortality coefficients (8). Fires also impact the forest sector indirectly, through owners' anticipations of future fires (9) and impacts on products prices (10). Model outputs are used to partition different sources of uncertainty in projections (11).

3.2.2. From burned areas to fire-induced mortality

Because the FFSM uses yearly time steps, we cumulate, for each pixel, BA from all fires during the fire season. BA in the fire activity model are assumed to affect both "forest" and "shrubland" land-use classes. Since the FFSM only considers forests, in each pixel, we distribute BA to each land use class proportionately to its cover share. Since yearly BA cannot exceed forest area, the difference is modelled to randomly spread to neighbouring pixels with unburned forest area. Due to the presence of natural breaks in the landscape, it is also unlikely that all forest within one single pixel will burn. Therefore, we set an upper limit to burned areas corresponding to 90% of forest area[37].

The spatial distribution of forest types and diameter classes within each pixel is unknown, as well as the location of burned areas. We apply the intermediate-complexity approach used in fire-enabled DGVMs (Li, Zeng, and Levis 2012; Hantson et al. 2016) and distribute BA to each strata (i.e. combinations of forest type ft and diameter class dc) proportionately to their area and volume shares. We subsequently define $m_{ft,dc,reg}$ as strata-specific mortality coefficients for volumes affected by fires, for each model region reg. Assuming that each unit volume is representative of its strata, timber volumes ΔV killed by fires are given by:

$$[10] \quad \Delta V_{ft,dc,px} = m_{ft,dc,reg} * V_{ft,dc,px} * k_{fire,px}$$

where $k_{fire,px}$ is the share of forest area affected by fires within a pixel px. Fire resistance varies across tree species (Fernandes et al. 2008; Pimont et al. 2014; Fréjaville et al. 2018) and species composition varies across regions. To take these factors into consideration, we defined

[37] This case is however extremely rare and is limited to pixels with low forest areas where a large fire is simulated to occur.

species-specific mortality coefficients $m_{sp,dc}$ (cf. subsection 3.2.3.) and computed regional mortality coefficients $m_{ft,dc,reg}$ as the weighted average of species-specific coefficients, in each region:

$$[11] \quad m_{ft,dc,reg} = \frac{1}{V_{ft,dc,reg}} * \sum_{sp \in ft} V_{sp,dc,reg} * m_{sp,dc}$$

Species composition was determined using National Forest Inventory data stratified by administrative region and diameter class category[38]. Because of the large number of species, only those representing 5% or more of forest volume in at least one region were kept (17 species, Appendix D.3). We considered pure broadleaf and pure coniferous forest types to be composed of a representative combination of broadleaf and coniferous species respectively, and mixed forest types are assumed to be composed of a representative combination of all species in the region.

3.2.3. Determination of species-specific coefficients

We chose values for species-specific mortality coefficients based on empirical findings from the literature and expert knowledge. We define baseline coefficient ranges based on Ryan and Amman (1994)'s generic model of post-fire tree mortality, widely used in fire effects software (Hood et al. 2018; Woolley et al. 2012; Hood et al. 2007), considering 60-70% crown volume scorched, i.e. a relatively high amount of damage typical of summer fires[39] (Appendix D4).

For pine species, we adapt coefficients based on empirical models of post-fire mortality developed in Portugal, France and Spain (Fernandes and Rigolot 2007; Fernandes et al. 2008; Pimont, Prodon, and Rigolot 2011; Pimont et al. 2014; Catry et al. 2013; Catry et al. 2010; Garcia-Gonzalo et al. 2011) and pay particular attention to values being consistent across species. Indeed, while most pines are to some degree "fire resistant" (e.g. *Pinus nigra*, *Pinus pinaster*), other are "fire toleraters" (e.g. *Pinus pinea*) and display lower average mortality rates, while others are "fire avoiders" and display high mortality rates (e.g. *Pinus halepensis*, *Pinus nigra laricio*), reflecting different strategies and plant traits (Keeley 2012; Fernandes et al. 2008). The empirical literature is scarcer for Mediterranean broadleaf species (*Quercus ilex*, *Quercus pubescens*). These species are known for having thinner bark but are able to resprout from dormant buds in stems or roots: we define coefficient values based on models of top-kill probability for resprouting species (Catry et al. 2010; Catry et al. 2013).

Empirical models have not yet been developed for temperate and sub-alpine species (*Abies alba, Fagus sylvatica*), but recent studies have garnered knowledge on relationships between fire regimes, tree traits and mortality (Conedera et al. 2010; Maringer et al. 2016; Dupire et al. 2019; Fréjaville et al. 2018; Fréjaville, Curt, and Carcaillet 2018). We attributed mortality coefficients based on such literature, assigning higher values than for "fire resistant" Mediterranean species and keeping values consistent across species groups, i.e. "fire tolerant" (*Larix decidua*), "fire intolerant" (*Abies alba*) and "fire sensitive" (*Fagus sylvatica*) species.

[38] We use the stratification proposed by IGN: small trees have diameter lower than 22.5cm, medium trees between 22.5 and 47.5cm and large trees above 47.5cm. www.ocre-gp.ign.fr.

[39] For example, Rigolot (2004) report average values of 70-75% for fires in South Eastern France (pine species), and Catry (2010, 2013) values in the 60-100% range for most species in Portugal (broadleaves and pine species), both in the case of summer fires.

Our ad-hoc coefficients, despite being inspired by the empirical literature, do not consider several important factors, such as forest structure and fuel load. Due to lower canopy and higher fuel continuity, coppices are more vulnerable to fires than high forests (Dupire et al. 2019). We increased mortality rates in broadleaf coppices by 20%, and by 10% in intermediate structure forests compared to their high forests counterparts.

Table 4.1 –Post-fire mortality coefficients for each forest type in the FFSM. Values are averaged over the whole study area (region-specific coefficients are implemented in the model).

Diameter (cm)	High forest			Intermediate structure		Coppice
	Broadleaf	Coniferous	Mixed	Broadleaf	Mixed	Broadleaf
<22,5	0,91	0,89	0,90	1,00	0,99	1,00
22,5-47,5	0,56	0,54	0,54	0,61	0,60	0,67
>47,5	0,35	0,28	0,30	0,38	0,33	0,42

3.3. Scenario building

A large part of uncertainty in climate forecasts comes from the choice of the climate model and assumptions on future radiative forcing (Hawkins and Sutton 2009). To explore several possible developments, we build fire histories using data from 5 different couples of Global Circulation Models (GCM) and Regional Circulation Models (RCM) under three radiative forcing levels (Appendix D5). The first two forcing levels correspond to Representative Concentration Pathways (RCP, IPCC 2014) RCP 4.5 (moderate warming) and RCP 8.5 (significant warming), and the third scenario corresponds to a continuation of current climate (no warming). This yields a set of 15 scenarios with fires, to which we added a baseline scenario where there are no forest fires.

For each scenario, the fire activity model is used to generate 30 fire histories for the years 1985-2100[40]. Each fire history is different due to stochastic factors in the fire model, but all are based on the same underlying climate simulation. Actual climate conditions display a high interranual variability and are generally considered stable only over longer periods, e.g. 30 years. Locally, dynamics in the forest sector can be heavily impacted by the timing of a shock such as an extreme fire season. To take this fact into account, we shuffled fire histories by performing random draws in 30-year moving windows. For "constant climate" scenarios, random draws were always performed in the same period (i.e., the historical period 1985-2015), resulting in a continuation of historical climate into the future.

Because agents in the management module of the FFSM anticipate future conditions (i.e. future fire mortality), fire histories are also needed for years beyond the simulation period. Given uncertainties regarding long-term climate evolution, we assumed forest owners to expect a linear evolution of yearly BA in their region beyond 2100. Anticipated fires were generated at the pixel level through the abovementioned procedure but from random draws in the 2070-2100 period (i.e. end-of-century climate), corrected by the relative difference between the expected regional trend and average burned areas in 2070-2100. Such anticipated

[40] The generation of raw, daily fire histories was performed with GCM-RCM simulation data retrieved from the EURO-CORDEX initiative subsequently downscaled to the 8km level following the procedure described in Fargeon et al. (2020) by co-authors at INRAE URFM. All other steps and adaptations for the FFSM were performed by Miguel Riviere.

fires will never actually happen and will not affect forest resources: their impact is limited to owners' replanting decisions in later stages of the simulation.

3.4. Data analysis and uncertainty partitioning

To illustrate the implications of introducing disturbances into the model, we focus on a few key variables. Metrics reported belong to two categories: stock variables (e.g. forest volumes) and flow variables (e.g. yearly harvests). As we highlight in the results section, impacts on the forest sector are quasi-cumulative, hence we focus on the end of the century period, i.e. 2070-2100 for flow metrics, 2100 for stock metrics. We proceed by scenario analysis and all values are reported as changes compared to the baseline. Because each scenario comprises multiple replications, we report both averages and standard deviations across replications.

Climate-induced uncertainties are usually separated into several categories (Hawkins and Sutton 2009; Lehner et al. 2020). *Climate scenario uncertainty* (radiative forcing uncertainty) is due to the lack of knowledge about future GHG emissions and their consequences for global warming. *Model uncertainty* (climate response uncertainty) arises from different climate models' responses to radiative forcing, which depend on initial conditions and modelling choices. *Internal variability* arises from the chaotic nature of climate processes at any point in time. Climate scenario uncertainty can be assessed by considering several levels of radiative forcing, model uncertainty by comparing the response of several models to a given forcing level, and internal variability by using several simulations with different initial conditions. This approach to uncertainty partitioning was recently adapted to fire danger prediction by Fargeon et al. (2020). While computations are generally performed on smoothed (usually decadal) data series for weather metrics, internal variability is computed at the yearly scale for fire metrics (i.e. *inter-annual variability*), which is relevant to investigate extreme fire years. Indeed, using FWI as a metric of fire danger, Fargeon et al. (2020) showed that inter-annual variability was the main source of uncertainty for the early to mid-21st century and still represented around 30% of uncertainty by 2100.

In order to assess how uncertainty propagates from climate projections and fire activity to dynamics in the forest sector, we extend the methodology to dynamics in the forest sector, i.e. FFSM outputs. While Fargeon et al. (2020) projected fire danger using, for each scenario, the mean model, we use ensembles of 30 replications. Similar ensembles are found in e.g. Lehner et al. (2020), but, while their replications correspond to runs of the same climate model with different initial conditions, our replications are due to stochasticity in the fire process. Keeping these differences in mind, we make the following adaptations (Figure 4.5). Prior to any calculation, we smooth data series with a 30-year Butterworth low-pass filter and Mann's (2008) adaptive padding approach. The resulting signal is called the "trend", and we compute inter-annual variability as the mean variance of residuals from this trend. We define *replication variability uncertainty* as the uncertainty arising from stochasticity in the fire process. We compute it as the mean variance of the trend across ensemble members, i.e. across replications of a given scenario. As in Lehner et al. (2020), we compute model uncertainty as the variance of ensemble means across climate models. Finally, we compute climate scenario uncertainty as the variance of ensemble means across climate scenarios, averaged over climate models. Because our fire histories are generated from random draws in 30-year windows, internal variability is not relevant[41].

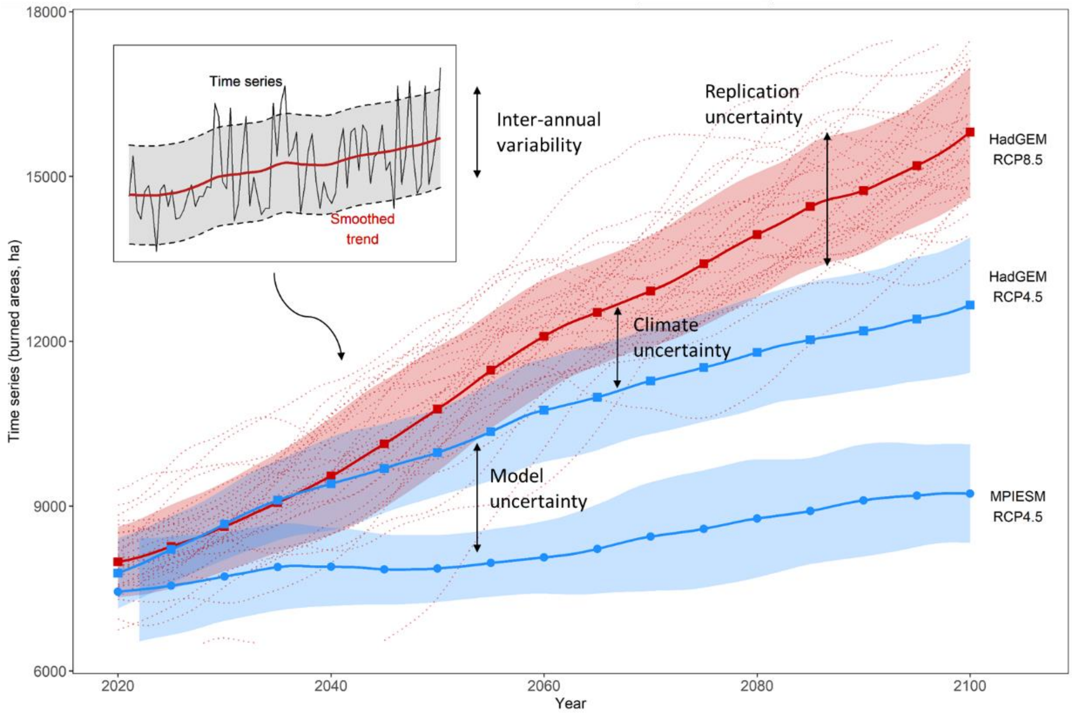


Figure 4.5 – Illustration of the different sources of uncertainty. Numerical values are taken for burned areas for scenarios Hadgem_rcp8.5, Hadgem_rcp4.5 and MPIESM_rcp4.5. The smooth (inset) is illustrated for the second replication of the Hadgem_rcp8.5 scenario.

4. Forest sector impacts of changing fire regimes

4.1. Overview of fire histories

FWI is the main driver behind our scenarios. Its average value during the fire season increases over the study area, going from 6.7 in the 1985-2015 period to 8.8 (+30%) and 11.2 (+67%) by the end of the century for the RCP 4.5 and RCP 8.5 scenarios respectively, with marked increases around the Mediterranean in the western half of the region (top maps in Figure 4.7). In the constant climate case, burned areas (BA) remain relatively stable throughout the simulation (around 6.600ha/year) while they increase steadily with a warming climate (Table 4.2). This increase is gradual over time: while cumulated BA are 12-13% higher in 2020-2060 regardless of the forcing level, they are 26% and 55% higher in 2070-2100 for RCP 4.5 and RCP 8.5 respectively.

BA is unevenly distributed among the 5 regions within the study area (cf. Appendix D.1, Table 4.2). PRO and AQU together represent 60% of BA while other regions represent each 15% or less. When considering the BA-to-forest area ratio, the southern PRO region is also the most affected, while northern regions are the least affected (AUV and RHO). Compared to the

[41] Internal variability could be computed by using Single Model Initial conditions Large Ensembles (SMILES, i.e. several runs of a given climate model with varying initial conditions) as inputs for the fire activity model. However, this would greatly increase computation time (e.g., SMILES with 10 members would yield 4500 FFSM simulations instead of 450) and is not realistic with a coupling to the FFSM.

constant climate case, the relative increase in mean annual burned areas is highest in southern regions (PRO, MID) than in other parts of the study area.

Region	Constant climate	RCP 4,5		RCP 8,5		Share
AQU	1527	1850	(+21%)	2258	(+48%)	23%
AUV	798	969	(+21%)	1176	(+47%)	12%
RHO	970	1159	(+19%)	1343	(+38%)	15%
PRO	2420	3167	(+31%)	3959	(+64%)	37%
MID	904	1188	(+31%)	1507	(+67%)	14%
France	**6619**	**8334**	**(+26%)**	**10242**	**(+55%)**	**100%**

Table 4.2 – Mean annual burned areas (ha/year) simulated for the end of the century period (2070-2100 multi-model, multi-replication means). Percentages in brackets indicate the relative increase in burned areas compared to the historical period, and percentages in the right-hand column indicate the regional distribution of burned areas, which stays relatively stable across scenarios.

In all scenarios, BA display a high inter-annual variability (Figure 4.6), which is due to natural variability in fire and climate processes. Due to the shuffling procedure, extreme fire years (peaks) happen at different moments. BA is also unevenly distributed across pixels, which is consistent with fires remaining a relatively rare event (Figure 4.7, bottom maps). Consistently with the evolution of FWI, the highest average BA are found in pixels close to the Mediterranean, and then in the western MID and AQU regions.

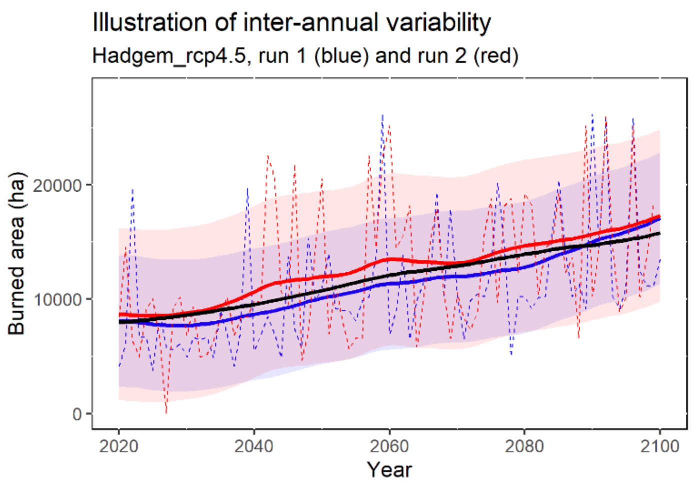


Figure 4.6 – Illustration of inter-annual variability in simulated yearly burned areas. Values are given for two replications of the same scenarios (dotted lines). Smoothed trends are shown as solid coloured lines, and the multi-replication mean as a solid black line. Shaded areas correspond to inter-annual variability.

There are important differences in BA depending on the climate model used, and these differences increase over time and with the forcing level (Appendix D.5). For the constant climate case, differences across models remain limited throughout the simulation, except for HadGEM, which yields slightly higher values. For warming climate cases, differences across models (other than HadGEM) remain limited in the first decades of the simulation. Model spread is highest in RCP 8.5 and all models show moderate to high increases in BA compared to the constant climate case. For the end of the century period, these changes range from +15% with CNRM to +92% with HadGEM, where BA reach 16000ha/year in 2100.

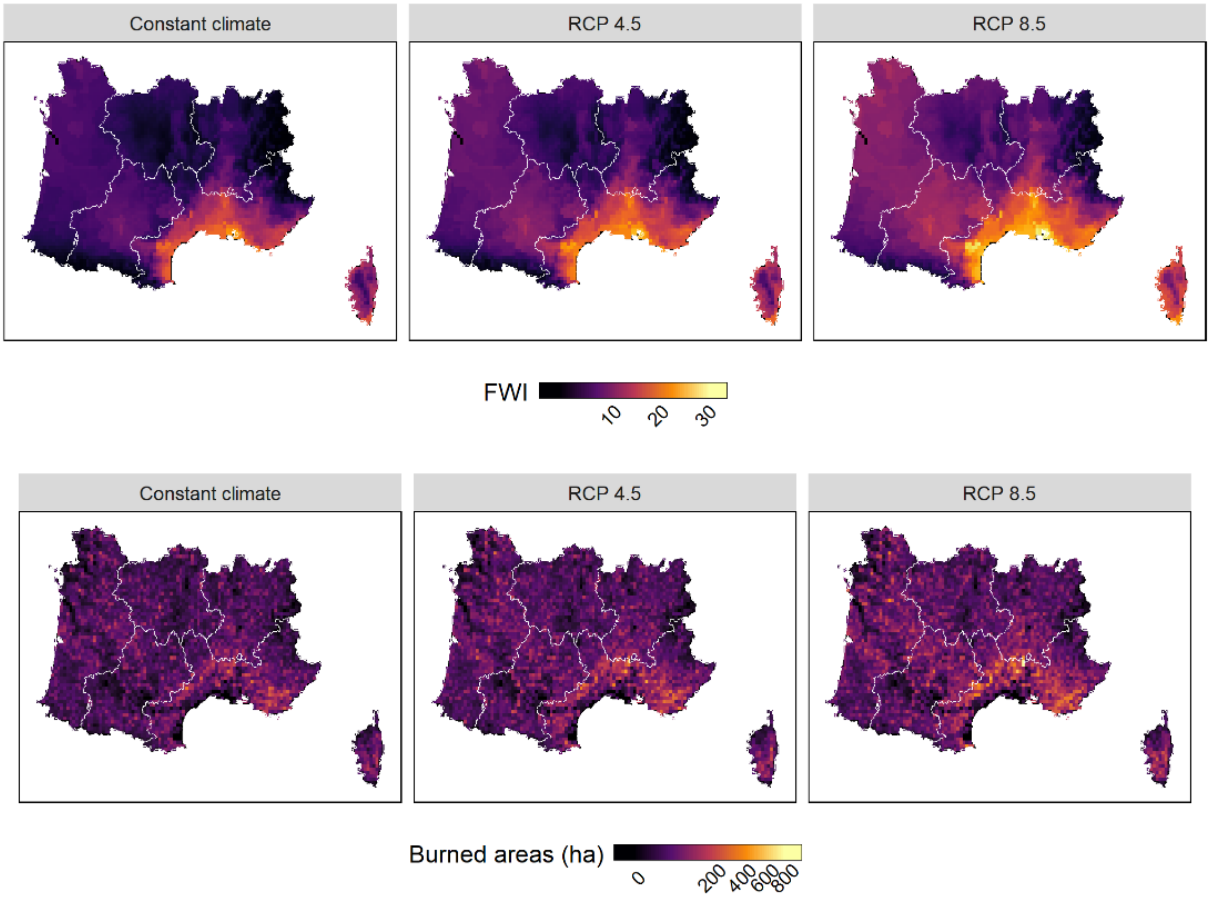


Figure 4.7 – Pixel repartition of simulated fire season FWI and burned areas. FWI are computed as multi-model 30-year mean values, on the historical (1985-2015, left panel) and end of century periods (centre and right panels, 2070-2100). Burned areas are computed as multi-model, 30-year mean cumulated values for the end of century period (2070-2100).

4.2. Forest sector dynamics

4.2.1. Impact on the resource

Results for forest sector dynamics are represented in Figures 4.8 and 4.9. Tree mortality rises as a result of introducing fires and, with a constant climate, mortality is 4.8% higher than in the baseline. Mortality is higher in warming climate scenarios than with a constant climate, but differences between RCP 4.5 and RCP 8.5 only appear the second half of the simulation. By the end of the century, fire-induced mortality in these scenarios is respectively 80% and 137% higher than in the constant climate case. This increase in mortality leads to declines in timber volumes. In BAU, forest volumes increase steadily in the study area, going from 1495 Mm3 to 2530 Mm3 in 2100. While volumes still expand in all other simulations, introducing fires with a constant climate leads to a 3.6% loss in forest volumes by 2100, and this decrease becomes stronger with a warming climate (4.7% in RCP 4.5, 5% in RCP 8.5).

Harvests in the FFSM are elastic to timber inventories, hence fires decrease harvest levels. Decreases are rather moderate in the first decades (less than 1%) but become more marked by the end of the century, with changes around -1% with a constant climate and -1.5% in RCP scenarios, up to -2% with model HadGEM and RCP 8.5. In northern France, we do not simulate fires and mortality is not affected. Harvests show marginal increases by up to 0.75%, and, as a consequence, timber volumes decrease by up to 0.53%.

Forest fires directly and indirectly (through harvests) affect carbon stocks in forest biomass, which decreases by 2.7% to 3.2% by 2100 with a constant climate. This fire-induced reduction is higher for RCP 8.5 (+26% by 2100) than for RCP 4.5 (+21%) compared to the constant climate case. This is also the case in northern France, but because fires only affect carbon stocks through harvests, changes are limited (less than -0.5%). Forest types in the FFSM have varying carbon densities and the distribution of forest types across pixels is heterogeneous, hence losses of carbon are not directly proportional to decreases in timber volume. Carbon stocks in wood products decrease slightly in both the study area (up to -1%) and northern France (-0.5%). While the former can be attributed to reduced harvests and supply, harvest levels actually go up in northern France. However, as described below, fires disrupt trade patterns (they are redirected towards the south), leading to lower carbon stocks in products pools in northern France as well.

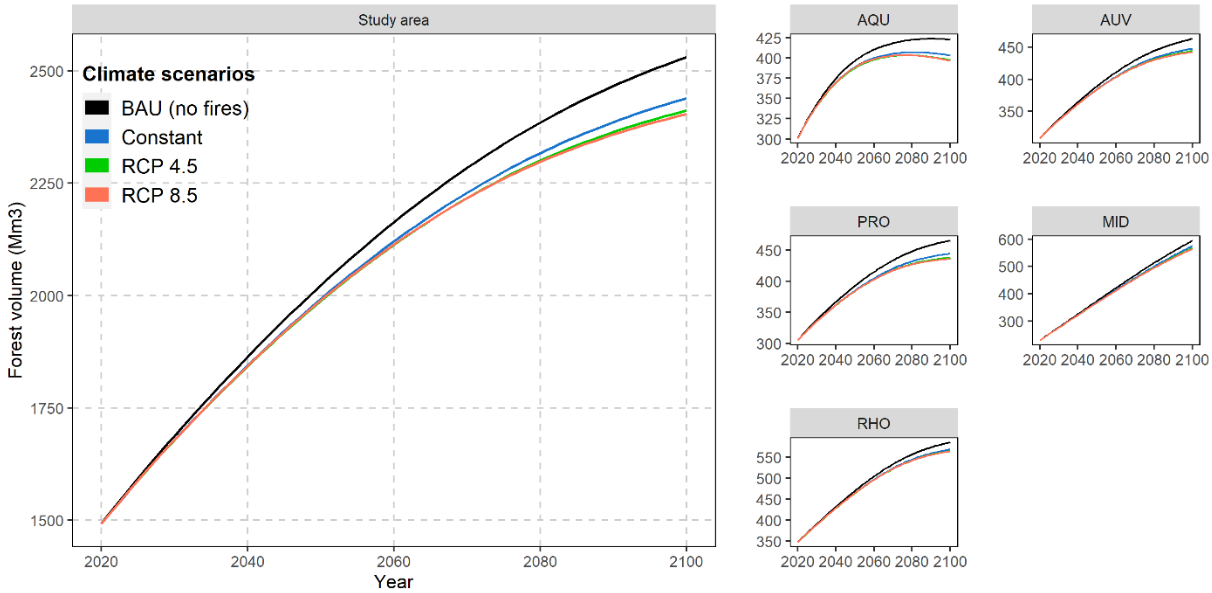


Figure 4.8 – Evolution of timber volumes in the study area (left) and in individual regions (right). Lines are multimodel multireplication means.

4.2.2. Impact on timber markets

Products supply is directly linked to harvests and declines in the study area. At first, this decrease remains limited (less than -0.5% in the first half of the simulation) regardless of the climate scenario and is comparable for all products. By the end of the century, reductions in supply become more significant (e.g. -0.7% to -1.7% for a constant climate), especially with a warming climate and for softwood products (up to -2.23%). In northern France, supply increases compared to the baseline and mirrors decreases in the study area, albeit with smaller relative changes. Increases in northern regions partly compensate reductions in the south through spatial equilibrium, and we indeed observe changes in trade patterns. On the one hand, trade fluxes from the study area to northern France go down (pulpwood and softwood), while trade fluxes from northern France to the study area go up (hardwood), reaching ±9% to ±15% by the end of the century.

As a consequence of reduced timber supply, products prices increase, especially in the long-term (+0.4% to +2.8%) and more strongly for softwood roundwood (consistently more than +2%), while it is more moderate for other products. Again, differences between climate scenarios are rather limited at first, and increase over time. In the study area, producer surplus retracts slightly at first (-0.1% to -0.3% in 2020-2059) but increases by the end of the century (up to +0.9%) with discrepancies across products. Indeed, while welfare does go up for softwood producers, it actually decreases for hardwood and industrial wood producers (Appendix D.6). For the former, increases in softwood prices offset reductions in harvests, while this is not the case for other products. In northern France, where both prices and harvests increase, producer surplus increases for all products, and the highest values are found for softwood again (up to +3.5%). Consumer surplus decreases in both areas, and total economic surplus is slightly reduced in the study area (-0.3%) and slightly increased in northern France (+0.15%). The difference in impacts for softwood products compared to hardwood products relates to how fires affect the resource, which is not homogenously distributed across the country. A majority of forest inventories suitable for softwood roundwood production are located in the study area (as opposed to Northern France), especially in AQU and also MID, both of which are heavily affected by fires in our projections. As a result, at the national level, a larger proportion of resources devoted to producing softwood products is affected by fires, e.g. with a constant climate, 1.5% by 2100, against 0.8% for hardwood products.

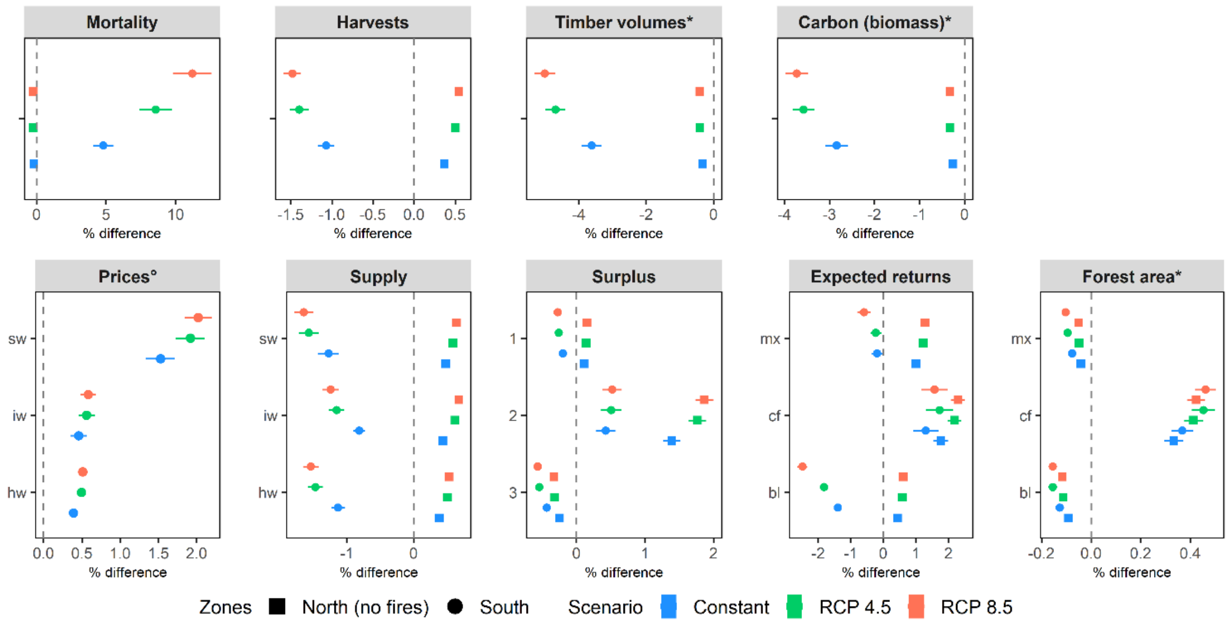


Figure 4.9 – Fire impacts on dynamics in the forest sector. Points represent averages for a given climate scenario and error bars indicate standard deviation across replications. Values are given for the end of century period (2070-2100), except for (*) where they are reported for year 2100. Prices (°) are given at national level. Products are (hw) hardwood roundwood, (iw) industrial wood and (sw) softwood roundwood; forest types are (bl) broadleaf, (cf) coniferous and (mx) mixed; surpluses are given for producers (2), consumers (3) and overall (1).

4.3. Forest management and landscapes

In the study area, expected returns at first decrease by -1% to -3% for all forest types, with limited differences across scenarios. Agents in the FFSM anticipate future environmental conditions, hence these reductions are attributable to expected future fire-induced mortality. On the opposite, expected returns in northern France remain very close to those in the baseline, albeit slightly higher due to increased prices. In the long-term, expected returns undergo contrasted evolutions depending on the forest type considered (Appendix D.8). Indeed, while they remain lower than in the baseline for broadleaf forests (-1.8% to -3.2%), they increase for coniferous forests (+1.1% to +2.4%) and reach values similar to the baseline for mixed forests (around -0.5%). These long-term changes can be explained by higher products prices, especially for softwood roundwood, which offset the anticipated mortality increases for forest types other than pure broadleaf. In northern France, no increase in mortality is expected and expected returns increase for all forest types (+0.5% to +3.1%). Changes in expected returns affect regeneration decisions after harvests, which marginally influences forest composition in the long run. By the end of the century, nationwide, the area of coniferous forests expands slightly by e.g. 0.4% to 0.6% (12.000 to 18.000 ha), while those of broadleaf and mixed forest area decrease.

4.4. Regional trends

Result trends generally hold at the regional level, even though some discrepancies must be noted (Appendix D.7). LAN and AQU, due to having the largest BA, are the regions most affected by losses of timber volumes, forest carbon and decreases in harvest levels. Besides, the absolute decrease in timber volumes expected in these regions occurs earlier than in the baseline: between 2067-2074 (against 2076) for the former, and between 2061-2077 (against 2077) for the latter. In other regions, forest volumes keep expanding and undergo relative decreases comparable to or lower than average changes in the study area. Surprisingly, while it only comes at the third place in terms of BA, MID displays the largest relative increase in mortality. This dynamic is due to the region having lower baseline mortality than other regions of the study area. As for the study area as a whole, consumer surplus decreases in all regions while, driven by increases in softwood producers' surplus, producer's surplus increases in 3 regions (MID, RHO and AUV). This increase is particularly strong in MID, where harvests actually increase following the resolution of spatial equilibrium, resulting in a higher total surplus for the regional forest sector. On the opposite, owing to larger reductions in inventories, harvests and supply, changes in producer surplus in AQU and PRO are respectively close to null and negative, leading to negative changes in total surplus.

5. The role of climate-induced uncertainties in model projections

Uncertainty in the evolution of BA is dominated from the onset by inter-annual variability, which accounts for more than 75% of uncertainty until 2060 (top row in Figure 4.10). Over time, other sources of uncertainty become more important and total uncertainty increases by 75.9% over the course of the simulation. By 2100, model and climate scenario uncertainty account for 18.6% and 26.1% of total variance respectively, but, owing to the high stochasticity of the fire process, inter-annual variability still represents 52.4% of total variance. These results are consistent with those highlighted for fire danger by Fargeon et al. (2020), even though the relative importance of inter-annual variability is higher for BA than for FWI and weather metrics. Replication uncertainty remains stable and only accounts for 2.8% to 4.5%

of total variance: once inter-annual fluctuations are removed, differences in BA across replications remain limited. Tree mortality shows a similar evolution (Appendix D.8), which is consistent with it being dependent on BA.

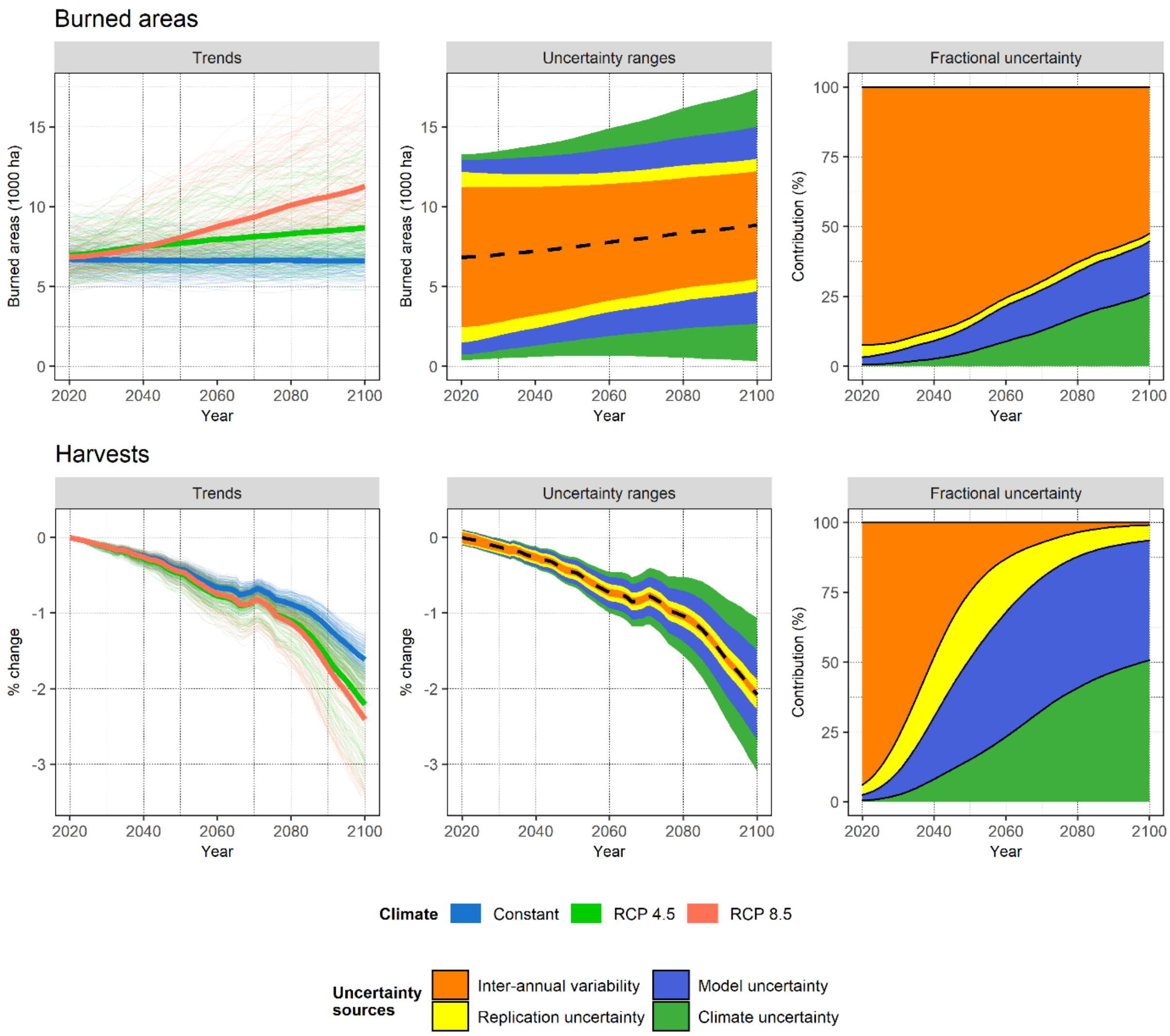


Figure 4.10 – Uncertainty partitioning for simulated projections of fire activity (burned areas, top) and forest sector dynamics (harvests, bottom). Left-hand boxes: multi-model, multi-replication trends (solid lines) and individual replications (thin lines). Middle boxes: uncertainty partitioning with 90% uncertainty ranges around the overall trend. Right-hand boxes: fractional uncertainty.

Uncertainty in the evolution of forest sector dynamics displays a different profile, which we illustrate for harvest levels (bottom row in Figure 4.10). In absolute terms, uncertainty starts at a low level, increases slowly at first but rapidly accelerates, with a 6-fold increase in the first half of the simulation and a strong surge (12-fold increase) in the second half. While, similarly to BA, inter-annual variability dominates total variance in the first years, its relative importance decreases more rapidly. It accounts for more than 50% of total variance only until 2039, for more than 25% until 2049 and accounts for less than 1% in 2100. On the other hand, model and climate scenario uncertainty rise strongly after the first decades. Model uncertainty increases first and keeps increasing in absolute terms throughout the simulation. In relative terms, it represents at least 25% of total uncertainty from 2042 onwards, peaks at 47.5% in 2072 and then goes down, reaching 42.9% in 2100. Scenario uncertainty expands in absolute and relative terms throughout the simulation, but later than model uncertainty. It represents at least 25% of total uncertainty from 2062 onwards and accounts for half of total uncertainty in 2100. Replication uncertainty increases steadily in absolute terms throughout the simulation. Its relative importance peaks around 24% between 2040 and 2050 and then decreases all the way to 2100, where it accounts for 5.5% of total variance.

Timber harvests, products supply and prices depend on one another, and uncertainties for supply and prices show profiles similar to harvests, with minor differences across products (Supplementary Material D.8). In the first half of the simulation, inter-annual variability has the highest relative importance for industrial wood supply and prices and the lowest for hardwoods, suggesting that market dynamics for hardwood products may be comparatively less prone to annual fluctuation when the resource is submitted to disturbances. We can also notice the higher relative importance of replication uncertainty in the evolution of supply and especially prices (compared to harvests), where it accounts for more than 10% of total uncertainty and reaches values above 30% mid-simulation. In the long-term, model and climate scenario uncertainty account for most of total uncertainty.

The FFSM is a deterministic model: all simulations start at the same point and start diverging only once fires are introduced. As a result, it does not come as a surprise to observe low levels of uncertainty at first for metrics other than BA and mortality. Fires only affect a small proportion of timber inventories every year, hence inter-annual fluctuations in BA, even though they may be very large, only marginally translate into inter-annual fluctuations in e.g. harvests. However, burned inventories are permanently removed from production and growth[42]: fires thus have a quasi-cumulative impact on dynamics in the forest sector. Such cumulative impacts are negligible in the first decades, where most of the uncertainty comes from (low) inter-annual fluctuations. As areas affected by fires accumulate and values diverge across replications, total uncertainty increases and other sources of uncertainty become more important. The cumulative manner in which fires affect the forest sector explains why differences across models and climate scenarios are mostly witnessed in later stages of the simulation.

Expected returns are annual metrics whose value depend on future fire-induced mortality[43] and do not depend on past values. As a result, they display uncertainty profiles similar to those of fire activity, i.e. a relatively high level of uncertainty from the onset, with a very important contribution of inter-annual variability and a rising contribution from model and scenario uncertainties (Supplementary material D.8). For coniferous and mixed forests however, trends from various models and climate scenarios intersect towards the middle and end of the simulation respectively. This results in lower contributions from climate and scenario uncertainties at these moments, and a higher contribution from replication uncertainty (20-30%).

[42] Burned areas regenerate but take many decades to reach pre-fire stock levels.
[43] In this application of the FFSM, owners are implemented to have perfect knowledge of future environmental conditions, including fire risk.

6. Avenues for improving fire modelling in the FFSM

6.1. Introducing land-use, land-cover and socioeconomic predictors into the fire activity model

A major limitation of our approach comes when predicting future fire activity outside the model's calibration area, assuming the weather-fire relationship remains valid in the future and in other areas. While the former is hard to overcome without using process-based models, we propose to tackle down the latter by introducing spatially-explicit land-use, land cover and socioeconomic (LULC-SE) predictors into the fire activity model. We explore this possibility by performing an exploratory analysis using Boosted Regression Trees (BRTs), a Machine Learning algorithm, with the objective to establish a relationship between fire occurrence, fire size and LULC-SE predictors[44].

6.1.1. LULC-SE determinants of fire activity

Statistical models of wildfire risk have generally focused on weather variables or fire danger indices as predictors. However, over the last years, an increasing number of studies have documented the relevance of also using spatialized LULC-SE predictors, especially in densely populated areas and for long-term forecasts (Costafreda-Aumedes, Comas, and Vega-Garcia 2017; Ganteaume et al. 2013; Mancini, Corona, and Salvati 2018; Julien Ruffault and Mouillot 2017).

LULC-SE predictors can be broadly separated into 3 categories. First, predictors related to human presence. Occurrence probabilities increase close to population centres, activity clusters (industry, agriculture, tourism) and along communication axes, even though large fires tend to occur in more remote locations. Landscape structure at the interface between human activities and wildland is also an important determinant of fire activity. Second, predictors related to landscape composition and the nature of fuels. For example, low sclerophyllous vegetation and coniferous trees may be more flammable than high forests and broadleaf trees respectively. Moreover, several studies have highlighted that, due to tourism, fire occurrence probability was higher in protected areas such as natural parks, or where touristic facilities are available. Third, predictors related to topography. Variables such as elevation and slope are commonly used in models, but they are often strongly correlated to LULC-SE predictor, e.g. fire occurrence probability will be high in lowlands, which also happen to be where urban centres are located. Such dynamics have been documented both for the case of Southern France (Ager et al. 2014; Opitz, Bonneu, and Gabriel 2020; Curt, Fréjaville, and Lahaye 2016; Julien Ruffault and Mouillot 2017; Ganteaume and Jappiot 2013) and for that of other Mediterranean countries (Moreira et al. 2011; Oliveira et al. 2012), including Italy (Mancini, Corona, and Salvati 2018), Spain (González-Olabarria, Mola-Yudego, and Coll 2015; Gallardo et al. 2016; Vilar et al. 2016), Portugal (Nunes, Lourenço, and Meira 2016), Greece (Kalabokidis et al. 2007) and Cyprus (Papakosta and Straub 2017).

LULC-SE predictor variables

From the literature outlined above, we established a list of commonly encountered predictors (Table 4.3), retrieved the corresponding data and computed predictor values at the scale of 8 km SAFRAN pixels in the PROMETHEE region using GIS software QGIS (QGIS.org 2020). To

[44] Results from this section will be used as a starting point to fit a new model with co-authors at INRAE URFM.

account for human influence, we included population density and the area of discontinuous urban fabric as predictors, as well as the amount of Wildland-Urban Interface (WUI), Wildland-Agricultural Interface (WAI) and Wildland-Grassland Interface (WGI). We took accessibility into account through two predictors: road density and railroad density, and also included the density of powerlines, which can be a source of ignition. To describe fuels, we used the share of wildland composed of shrubland, and the share of high forest composed of pure coniferous forests. The presence of protected and potentially touristic zones was accounted for with the area of Natura 2000 sites. Since our aim is to gain understanding about relationships between model behavior and predictors, we chose to exclude topography from our exploratory analysis.

Table 4.3 – LULUC-SE variables used in the exploration analysis

Variable	Computation	Data source
Wildland area (WA)	Sum of area	Corine Landcover (CLC, classes 31 & 322-324)
Share of shrubland Share of coniferous forest	Sum of area, as a share (%) of WA	CLC (322-324) CLC (311)
Road density[45] Railroad density Powerline density	WA within a 200m buffer around roads railroads and powerlines.	IGN Routes 500 IGN BD Carto
Population density	Number of inhabitants/km²	INSEE
Discontinuous urban area	Sum of area with a discontinuous urban fabric	CLC (12)
Wildland Urban Interface Wildland Agriculture Interface Wildland Grassland Interface	WA within a 200m buffer of Urban, Agricultural or Grassland LU	CLC (11-12) CLC (21, 22, 24) CLC (23, 321)
Protected areas (Natura 2000)	Sum of area	European Environment Agency

Human activity is mostly located along the coast and in the Rhône valley, where population density, urban area and WUI are highest (Appendix D.9). Wildland in these areas is dominated by shrubland, with relatively high areas of interface with agricultural activities (WAI) other than pastoral activities. Although main roads are located in lowland areas, road density appears highest in more remote locations due to the high coverage of such areas with numerous, smaller roads. On the opposite, railways and powerlines follow major roads, connecting population centres through lowlands and valleys. The hinterland (outside the Rhône valley) is characterised by lower human presence but higher WA, with a lower share of shrubland and a higher share of forests, especially coniferous forests when elevation increases. Most of WGI area is located in these more remote locations due to the presence of pastures.

Dependent variables

Our analysis seeks to explore relationships between fire occurrence and fire size as modelled by the fire activity model and LULC-SE predictors. Four models are built: one for each fire size threshold in the fire size model (10, 100 and 1000ha) and one for fire occurrence. For fire size,

[45] Because the fire activity model assumes fires only start on wildland area (WA), we computed most of our variables as areas of WA within a buffer linked to the item of interest, e.g. WA within a buffer around road networks.

the dependent variable is a binary equal to 1 when the observation corresponds to a fire larger than the threshold, 0 otherwise, and the exceedance probability simulated by the fire size model was added as a predictor.

For fire occurrences, the observation dataset contains a very high number of pixel-days unsuitable for an exploratory analysis. Instead, we use the occurrence model's pixel spatial effect as the dependent variable, i.e. $i(X,Y)$ in equation 1. Because WA is one of the occurrence model's two original predictors and a LULUC-SE predictor, we added its partial effect, i.e. $f(WA)$ in equation 8, to the dependant variable using the logarithm's additive decomposition property. Hence, the dependent variable is not fire occurrence itself, but the partial response of the logarithm of the expected number of fires to wildland area and pixel location, i.e. $\log\big(i(X,Y)\big) + \log(f(WA))$. When this variable takes positive (negative) values, it means the occurrence model base on FWI alone tends to underestimate (overestimate) fire count. As shown in Appendix D.9, this spatial effect is generally positive in lowland areas, but negative in remote locations.

6.1.2. Exploration of spatial effects with Boosted Regression Trees

Boosted Regression Trees (BRTs) is a machine-learning (ML) algorithm increasingly used as a substitute to traditional statistical modelling in environmental sciences (J. Elith, Leathwick, and Hastie 2008), including for fire activity analysis (Costafreda-Aumedes, Comas, and Vega-Garcia 2017). While statistical modelling starts by assuming the existence of a relationship between variables and subsequently estimates model parameters from empirical data, ML aims at directly learning relationships by identifying patterns within the data. The main advantages of BRT models include their ability to process correlated variables, to detect non-linearities and their generally good performance for analysing complex relationships (J. Elith, Leathwick, and Hastie 2008; De'ath 2007). In many instances, BRT and other ML algorithms have been shown to perform better than classical statistical models to explain and predict data patterns (Marcos Rodrigues and De la Riva 2014; Oliveira et al. 2012). Due to the aforementioned possibilities, they are well-suited for exploratory analyses with many variables (Feld, Segurado, and Gutiérrez-Cánovas 2016).

BRT is based on two pre-existent methods: regression trees (RT) and boosting. A RT model establishes binary splits of the predictor space, fitting the mean response within each subspace to minimise the sum across subspaces of squared differences between responses and their means. The tree starts with a single split (2 subspaces), and new splits are performed in an iterative manner. At the end of the process, the tree is pruned by removing the weakest splits through V-fold cross-validation. A RT model usually has lower predictive performance than statistical models. Boosting is a method used to improve model performance by iteratively building new models. In the case of BRT, new RTs are fitted to the previous RT model's residuals, and the final model is a linear combination of all RTs. Boosting is stochastic, and each RT is fitted on a different random subset ("bag fraction") of the data. While a single RT is easy to interpret due to its binary nature, BRT models are based on hundreds of individual RT and are harder to interpret directly.

We fitted BRT models in software R using package dismo (Hijmans et al. 2017). We set the bag fraction at 0.5 (recommended values range from 0.4 to 0.6) and determined the optimal number of trees with the gbm.step function, which uses 10-fold cross-validation. Following recommendations by Elith, Leathwick, and Hastie (2008) and Elith and Leathwick (2015), the learning rate (i.e. the contribution of each RT to the final BRT model) was chosen to reach at least 1000 trees. Then we used the gbm.simplify function to identify and drop the least relevant predictors. A logistic link was used for fire size models, and a Gaussian link for the fire occurrence model. The relevance of LULC-SE predictors is assessed through two metrics: (1) the relative influence of each predictor variable, and (2) partial dependence functions of the dependent variable to each predictor. The former is computed as a weighted average of the number of times each predictor is chosen in individual tree splits, the latter illustrates a given predictor's influence on the dependent variable, taking into account the (fixed) average influence of all other predictors.

6.1.3. Results

Occurrence model

The BRT model built for the occurrence model's spatial effect explains 52.7% of deviance and comprises 3150 trees. Dropped predictors were the density of power lines and the density of railroads. The variable with highest relative importance is wildland area (WA, 35.8%, Table. 4.4), which is consistent with the literature and with the model being built so that fires only ignite on wildland land-use classes. We observe a sharp drop in relative influence for other predictors. Four predictors have a relative influence in the 9-10% range: shrubland ratio, road density, the area of discontinuous urban fabric and population density. Other predictors have relative influences below 6%. WUI has been highlighted in many publications as very relevant to explaining fire activity patterns (Julien Ruffault and Mouillot 2017; M. Rodrigues, de la Riva, and Fotheringham 2014; Badia, Serra, and Modugno 2011), hence its relative unimportance here is surprising. However, discontinuous urban fabric, which we used as a surrogate metric, stands out in our analysis. WUI is often computed at finer scales than our 8km pixels: our scale may be ill-adapted to the inclusion of this metric.

The occurrence model's spatial effect responds negatively to WA (Figure 4.11), with a saturating effect for high values. This is consistent with the partial response of fire occurrence probability to WA (Pimont et al. in print), and suggests the occurrence model based on FWI alone underestimates occurrence probability in sparsely forested areas. Partial responses to the next four predictors show (mostly) monotonous, increasing relationships. This suggests that the model underestimates fire occurrence probability in locations with significant human presence and traffic (high population and road densities), and in areas where building intermingle with vegetation, such as loosely built-up suburbs where wildland is mostly composed of non-woody sclerophyllous vegetation. These results are consistent with the literature. The last graph shows a negative response to the presence of Natura 2000 sites, hinting at an overestimation of occurrence probabilities in pixels where large areas have Natura 2000 status. The literature generally highlights the opposite effect due to touristic frequentation of such sites (Costafreda-Aumedes, Comas, and Vega-Garcia 2017).

Table 4.4 – Relative influence of predictors for the fire occurrence BRT model

Predictor	Relative influence
Wildland area	35,8
Shrubland ratio	11,5
Road density	10,6
Population density	9,0
Discontinuous urban fabric	8,9
Natura 2000 area	6,0
Coniferous ratio	5,2
WAI	4,8
WGI	4,4
WUI	3,7
Powerline density	dropped
Railroad density	dropped
Deviance explained (%)	52,7
Number of trees	3150

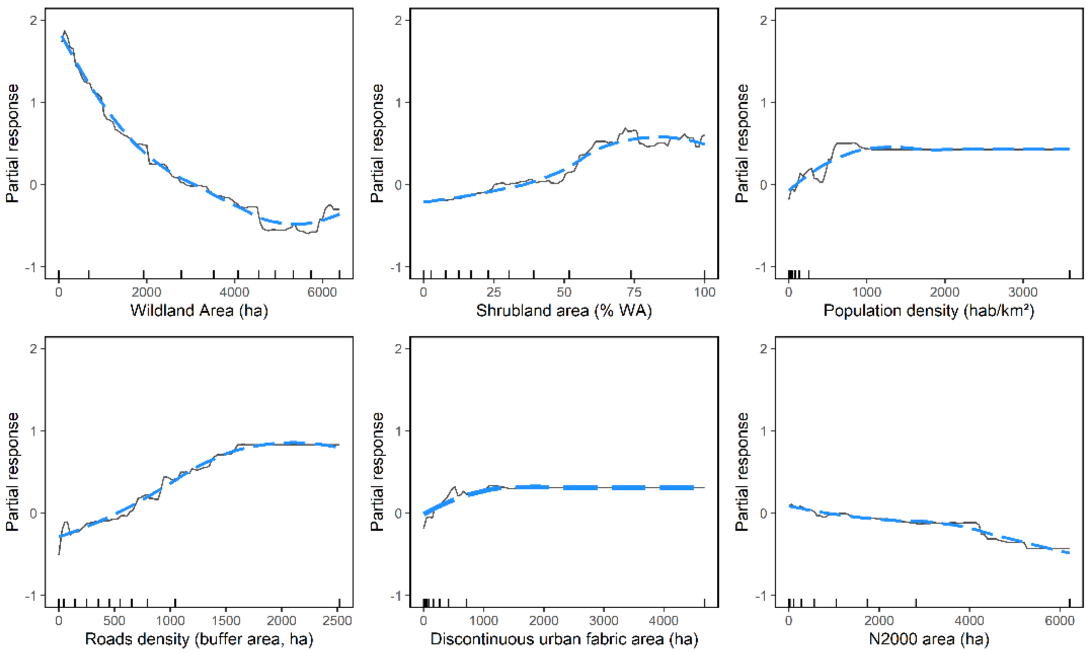


Figure 4.11 – Partial response functions for the BRT model built on the occurrence model's spatial effect. Smooths (blue) are added as visual aids. Rugs on the x axis indicate deciles.

Fire size model

BRT models for fire size only explain 7 to 13% of deviance, hinting at the difficulty of improving size modelling performance by adding LULC-SE variables (Table 4.5). Regardless of fire size thresholds, exceedance probability has the highest relative importance (34 to 93%) and population density comes in at the second place, albeit with a much lower relative importance (5.8 to 11.4%). Except for the 10ha size threshold, other predictors have very low relative importance.

Table 4.5 – Relative importance of predictors in fire size BRT models.

Predictor	Size threshold		
	10ha	100ha	1000ha
Exceedance probability	34,3	75,4	93,2
Population density	11,4	7,1	5,8
Wildland area	8,3	1,8	0,1
WAI	7,4	1,3	0
WGI	6,2	1,0	0
Coniferous ratio	5,9	1,6	0,3
Shrubland ratio	4,6	2,0	0,1
Powerline density	4,5	1,3	0,0
Natura 2000 area	4,0	1,5	0
Discontinuous urban fabric	3,6	0,6	0,1
Road density	3,4	0,9	0,0
Railroad density	3,4	4,7	0,5
WUI	3,0	0,7	0
Deviance explained (%)	**7,3**	**13,3**	**7,9**
Number of trees	1600	1000	1300

Caution is required when interpreting partial response functions, especially when predictors have heterogeneous distribution and the number of observations is low. Since a limited amount of fires was available for the 100ha and 1000ha thresholds, we focus on 10ha fires. Partial response graphs are harder to interpret and show almost flat and non-monotonous relationships for predictors other than exceedance probability (Figure 4.12). However, focusing on low to intermediate predictor values (where most observations are located), we observe a negative influence of population density and WAI on fire size and a positive influence of WGI and coniferous share. Coniferous forests and pastoral activities are both usually located in relatively remote, often mountainous locations. In such areas, low accessibility and landscape homogeneity may favour larger fires. On the opposite, areas with high population densities and non-pastoral agricultural activities are usually well-connected and well-monitored, favouring smaller but more numerous fires (Moreira et al. 2011; Ganteaume et al. 2013). In the end however, the influence of such variables remains marginal.

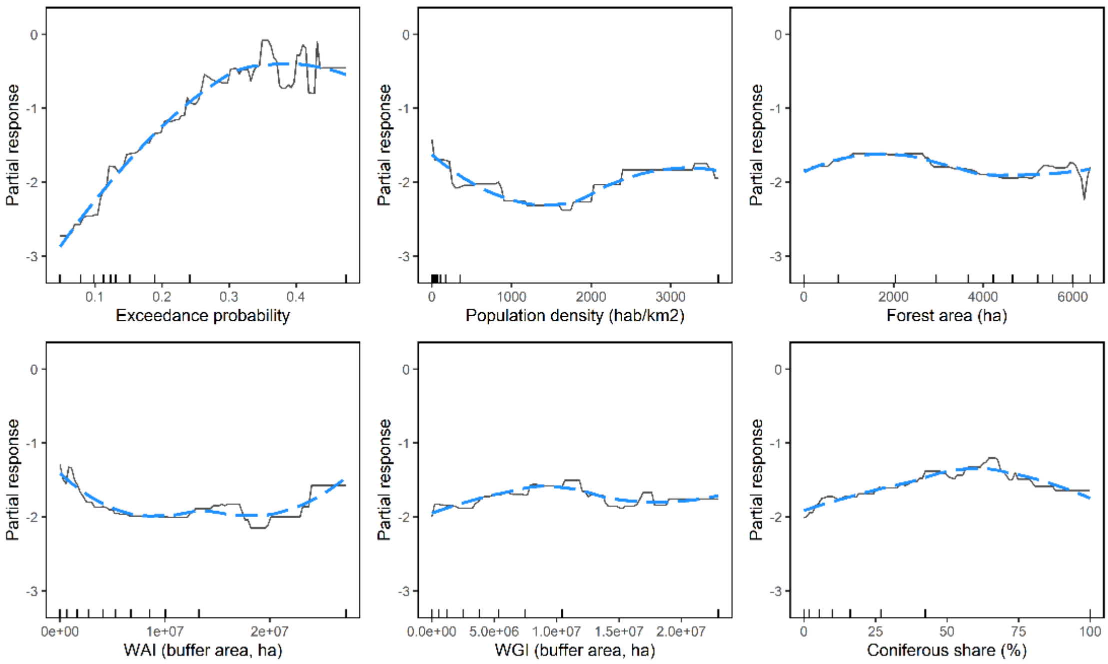


Figure 4.12 – Partial response functions for the BRT model built for the 10ha fire size model. Smooths (blue) are added as visual aids. Rugs on the x axis indicate deciles.

6.2. Other avenues for improvement

Even though we identify the inclusion of LULC-SE predictors as a major avenue for improvement, several other items are part of our research agenda. These relate to (1) the use of climate simulation data, (2) fire effects modelling and (3) scenario building.

First, our assessment of model variability uncertainty is based on 5 GCM-RCM couples selected to show different outcomes for the future (Fargeon et al. 2020), hence we potentially overestimate model uncertainty. To improve quantification of model uncertainty, future updates will either use a larger set of models, which is becoming common in the climate science literature (IPCC 2015), or models representative of standard deviation within such a set. At the moment this manuscript was written, we only had access to climate data up to 2100, which constrained the modelling of forest owners' anticipation of post-2100 fires. Future implementations will use post-2100 climate data as well. Besides, we shuffled fire histories over 30-year periods to avoid extreme fire seasons systematically occurring at the same moment. Results show that fire impacts are marginal but cumulative: shuffling fire histories may not be needed. We will test opportunities to remove this step in future implementations.

Second, we modelled fire impacts through an intermediate complexity approach rooted in large-scale vegetation modelling, empirical evidence and expert advice, which is nonetheless limited by several factors. The FFSM discriminates between diameter classes but does not model biomass in non-stem compartments, e.g. roots and the forest floor, which and are also affected by fires (Hood et al. 2018; Bär, Michaletz, and Mayr 2019). Neither did we discriminate between biomass directly combusted and biomass killed and transferred to the litter. These limitations could be overcome by refining the FFSM's ecological component or coupling it to growth simulators. Fire impacts are rarely identical across fire events and, in addition to tree traits, also depend on e.g. fire intensity and topography. While such factors are indirectly considered by our use of empirical findings, their explicit inclusion may require the use of process-based models. In the end, the FFSM remains a bio-economic model of the forest sector, i.e. an inventory model with economic considerations, and not a vegetation nor a fire effects model. Addressing the limitations mentioned above would change the nature of the model and significantly increase model complexity. While this does not preclude going down this road, it raises questions regarding tradeoffs modelers need to address regarding model improvement and the challenges faced when performing interdisciplinary research. In the meantime, such limitations must be kept in mind when drawing conclusions from simulation results, which need to be considered together with those obtained with different methodologies and not used in isolation to provide guidance.

Third, our focus was on methodological challenges, i.e. model coupling and implications for model behaviour, and we considered the impacts of changing fire regimes all other things being equal. Climate change is also expected to impact forest growth and mortality (Reyer et al. 2014; Taccoen et al. 2019) and other disturbances such as droughts and pathogens are also expected to become more common, with potential interactions with fires and climate change (Seidl et al. 2017; Reyer et al. 2017; Lindner et al. 2010). Besides, for a given forcing level, different socio-economic pathways are possible, with e.g. different impacts on land use or timber markets (Daigneault et al. 2019). Once methodological aspects have been covered, we aim at developing more detailed prospective scenarios integrating such aspects in order to conduct more realistic impact assessments. In particular, introducing the forest's growth response to climate change into the FFSM has been a pending challenge for a few years and has so far been addressed with scenario analysis (Lobianco et al. 2015) and statistical models (Delacote et al., in print). In the months to come, we seek to explore possibilities of using forest growth simulators as a way of introducing these impacts, a solution which may allow investigating changes in management practices as well.

7. Conclusion

Owing to their deterministic nature and high degree of spatial aggregation, large-scale models of the forest sector generally eschew explicit representations of natural disturbances and, more generally, have difficulty integrating aspects linked to risk and uncertainty. In this chapter, we introduced localized, stochastic fire disturbances into the French Forest Sector Model by means of a coupling with a probabilistic model of fire activity developed for Southern France. By doing so, we were able to assess implications for the forest sector of climate-induced changes in fire regimes as well as to identify and quantify different sources of climate-related uncertainty in projections in order to inform forest policy.

Projections were carried out for two "warming climate" cases (RCP 4.5 and 8.5) and, while differences with a "constant climate" case can be witnessed early, divergences between the two forcing levels only appear several decades into simulations. Burned areas are expected to increase by up to 55% (RCP 8.5) in Southern France by the end of the century. This evolution translates into increases in forest mortality and decreases in marketable timber volumes, also causing decreases in timber supply. Losses of timber inventory reach up to -5% (126Mm^3) by 2100 compared to the baseline, with fire-induced losses representing 14% of annual inventory growth in Southern France over the end of the century period (2070-2100). Due to their heterogeneous repartition nationally, softwood resources are relatively more affected than hardwood resources, and softwood products undergo larger increases in price. As a result, while revenues decrease for hardwood roundwood producers, they increase for softwood producers and forward-looking owners marginally increase investments in coniferous forests nationwide. Our model is spatially explicit and results highlight that more severe outcomes are to be expected around the Mediterranean as well as in the southwestern Aquitaine region. Tradeoffs between economic and environmental objectives may be more pronounced in the latter region, which concentrates a dynamic timber industry centred on monospecific pine plantations, particularly prone to fires and potential pathogens. Fires also have environmental consequences. Compared to the baseline, *in situ* carbon stocks decrease by up to 4.9% in our simulations, and carbon losses are up to 31% higher (RCP 8.5) compared to the constant climate case. Forests are generally presented as a natural carbon sink and climate policy often relies on the forest sector to compensate residual GHG emissions in the long term (Quinet 2019). Even though the actual figure will depend on factors not taken into account here (e.g. fire prevention and mitigation measures), our results question the validity of such assumptions in a context where not only fires but also other disturbances are expected to become more frequent and more intense (Seidl et al. 2017).

We adapted uncertainty partitioning methods to assess how different sources of climate-driven uncertainty propagate from the climate-fire system to dynamics in the forest sector. Similarly to fire danger (FWI, Fargeon et al. 2020), uncertainty in fire activity (burned areas) is dominated throughout the simulations by inter-annual fluctuations, and in later decades by uncertainty due to the choice of climate models and forcing levels. Fires only affect a limited proportion of forest resources each year but affected areas are removed from production for decades. Impacts on the forest sector are marginal but quasi-cumulative: uncertainty starts at a very low level, surges over a few decades, and inter-annual fluctuations in fire activity only marginally propagate to the forest sector. Uncertainty related to the choice of climate models and forcing levels increase strongly in later stages of the simulation and account for more than 80% of uncertainty in forest sector dynamics by 2100. This result stresses the importance of considering multiple climate outlooks in order to present of wide array of possible futures to policymakers. Even though it is never predominant, uncertainty due to stochasticity in the fire process remains at an intermediate and relatively stable level and represents 5-35% of total uncertainty, peaking in the medium-term. This result confirms the importance of considering variability in disturbance processes and validates our probabilistic approach to wildfires. Finally, we also explored ways to improve fire activity modelling by introducing LULC-SE predictors: population and road densities as well as the area covered in shrubland appear promising, and their investigation is part of our future research agenda.

Beyond forestry, climate issues and the future are often explored with detailed, bottom-up models of the energy or agricultural sectors. Like FSM, because of their large size and computational complexity, these models are often deterministic and rely on scenario analysis and inter-model comparisons to assess uncertainties (Prieg and Yumashev 2020)[46]. In this broader context, our work, through an illustration based on forestry and wildfires, illustrates how a probabilistic approach can be used to propagate and assess uncertainties in such a model. Our results reaffirm the importance of considering uncertainties related to climate processes when performing prospective analyses with large-scale bio-economic models: uncertainties due to general outlook trends, but also those due to the inherent variability of processes at stake. This chapter also showcases the potential of using bio-economic modelling

[46] On the opposite, top-down IAMs are usually more compact and systematic probabilistic uncertainty analyses are common.

together with modelling paradigms from natural sciences to inform policymaking on complex environmental questions pertaining to both ecological and economic dynamics.

References

Abatzoglou, John T., A. Park Williams, and Renaud Barbero. 2019. Global Emergence of Anthropogenic Climate Change in Fire Weather Indices. *Geophysical Research Letters* 46 (1): 326–36.

Adams, Darius M, and Gregory S Latta. 2005. Costs and Regional Impacts of Restoration Thinning Programs on the National Forests in Eastern Oregon. *Canadian Journal of Forest Research* 35 (6): 1319–30.

Ager, A. A., H. K. Preisler, B. Arca, D. Spano, and M. Salis. 2014. Wildfire Risk Estimation in the Mediterranean Area. *Environmetrics* 25 (6): 384–96.

Arora, Vivek K., and George J. Boer. 2005. Fire as an Interactive Component of Dynamic Vegetation Models. *Journal of Geophysical Research: Biogeosciences* 110 (G2): n/a-n/a.

Averett, Nancy. 2016. Smoke Signals: Teasing out Adverse Health Effects of Wildfire Emissions. *Environmental Health Perspectives*. Public Health Services, US Dept of Health and Human Services.

Badia, Anna, Pere Serra, and Sirio Modugno. 2011. Identifying Dynamics of Fire Ignition Probabilities in Two Representative Mediterranean Wildland-Urban Interface Areas. *Applied Geography* 31 (3): 930–40.

Bär, Andreas, Sean T. Michaletz, and Stefan Mayr. 2019. Fire Effects on Tree Physiology. *New Phytologist*. Blackwell Publishing Ltd.

Barbero, Renaud, John T Abatzoglou, François Pimont, Julien Ruffault, and Thomas Curt. 2020. Attributing Increases in Fire Weather to Anthropogenic Climate Change Over France. *Frontiers in Earth Science* 8.

Beaussier, Thomas. 2020. Évaluation Économique et Environnementale Du Développement Régional d'une Filière En Interaction Multi-Secteur et Multi-Échelle : Cas de La Filière Forêt-Bois Du Grand Est. UNIVERSITÉ DE LORRAINE.

Bedia, J., S. Herrera, A. Camia, J. M. Moreno, and J. M. Gutiérrez. 2014. Forest Fire Danger Projections in the Mediterranean Using ENSEMBLES Regional Climate Change Scenarios. *Climatic Change* 122 (1–2): 185–99.

Brown, Hutch. 2001. POLICY INITIATIVES IN WILDLAND FIRE MANAGEMENT. *• Fall*. Vol. 61.

Buongiorno, Joseph, and Craig Johnston. 2018. Effects of Parameter and Data Uncertainty on Long-Term Projections in a Model of the Global Forest Sector. *Forest Policy and Economics* 93 (May): 10–17.

Butry, D. T., D. E. Mercer, J. P. Prestemon, J. M. Pye, and T. P. Holmes. 2001. What Is the Price of Catastrophic Widlfire? *Journal of Forestry* 99 (11): 9–17.

Cardona, Omar Dario, Maarten K. Van Aalst, Jörn Birkmann, Maureen Fordham, Glenn Mc Gregor, Perez Rosa, Roger S. Pulwarty, et al. 2012. Determinants of Risk: Exposure and Vulnerability. In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*, 9781107025:65–108. Cambridge University Press.

Carvalho, A., M. D. Flannigan, K. Logan, A. I. Miranda, and C. Borrego. 2008. Fire Activity in Portugal and Its Relationship to Weather and the Canadian Fire Weather Index System. *International Journal of Wildland Fire* 17 (3): 328–38.

Catry, F. X., F. Rego, F. Moreira, P. M. Fernandes, and J. G. Pausas. 2010. Post-Fire Tree Mortality in Mixed Forests of Central Portugal. *Forest Ecology and Management* 260 (7): 1184–92.

Catry, Filipe X., Juli G. Pausas, Francisco Moreira, Paulo M. Fernandes, and Francisco Rego. 2013. Post-Fire Response Variability in Mediterranean Basin Tree Species in Portugal. *International Journal of Wildland Fire* 22 (7): 919–32.

Caurla, Sylvain, Vincent Bertrand, Philippe Delacote, and Elodie Le Cadre. 2018. Heat or Power: How to Increase the Use of Energy Wood at the Lowest Cost? *Energy Economics* 75 (September): 85–103.

Caurla, Sylvain, Serge Garcia, and Alexandra Niedzwiedz. 2015. Store or Export? An Economic Evaluation of Financial Compensation to Forest Sector after Windstorm. The Case of Hurricane Klaus. *Forest Policy and Economics* 61: 30–38.

Chatry, Christian. 2010. Rapport de La Mission Interministérielle Changement Climatique et Extension Des Zones Sensibles Aux Feux de Forêts Établi Par.

Chudy, Rafal P., Hanne K. Sjølie, and Birger Solberg. 2016. Incorporating Risk in Forest Sector Modeling – State of the Art and Promising Paths for Future Research. *Scandinavian Journal of Forest Research* 31 (7): 719–27.

Conedera, Marco, Lara Lucini, Eva Valese, Davide Ascoli, and Gianni Boris Pezzatti. 2010. Fire Resistance and Vegetative Recruitment Ability of Different Deciduous Trees Species after Low-to Moderate-Intensity Surface Fires in Southern Switzerland. *VI International Conference on Forest Fire Research*, no. November 2015.

Costafreda-Aumedes, Sergi, Carles Comas, and Cristina Vega-Garcia. 2017. Human-Caused Fire Occurrence Modelling in Perspective: A Review. *International Journal of Wildland Fire*.

Couture, Stéphane, and Arnaud Reynaud. 2011. Forest Management under Fire Risk When Forest Carbon Sequestration Has Value. *Ecological Economics* 70 (11): 2002–11.

Curt, Thomas, Thibaut Fréjaville, and Sébastien Lahaye. 2016. Modelling the Spatial Patterns of Ignition Causes and Fire Regime Features in Southern France: Implications for Fire Prevention Policy. *International Journal of Wildland Fire* 25 (7): 785–96.

Daigneault, Adam, Craig Johnston, Anu Korosuo, Justin S Baker, Nicklas Forsell, Jeffrey P Prestemon, and Robert C Abt. 2019. Developing Detailed Shared Socioeconomic Pathway (SSP) Narratives for the Global Forest Sector. *Journal of Forest Economics* 34 (1–2): 7–45.

De'ath, Glenn. 2007. Boosted Trees for Ecological Modeling and Prediction. *Ecology* 88 (1): 243–51.

Delacote, Philippe, Antonello Lobianco, Sylvain Caurla, Jean-Daniel Bontemps, Anna Lungarska, Pierre Mérian, Miguel Riviere, and Ahmed Barkaoui. n.d. The Loop Effect : How Climate Change Impacts the Mitigation Potential of the French Forest Sector. *Journal of Forest Economics*, 1–64.

Dupire, Sylvain, Thomas Curt, Sylvain Bigot, and Thibaut Fréjaville. 2019. Vulnerability of Forest Ecosystems to Fire in the French Alps. *European Journal of Forest Research* 138 (5): 813–30.

Dupuy, Jean-luc, Hélène Fargeon, Nicolas Martin-StPaul, François Pimont, Julien Ruffault, Mercedes Guijarro, Carmen Hernando, Javier Madrigal, and Paulo Fernandes. 2020. Climate Change Impact on Future Wildfire Danger and Activity in Southern Europe: A Review. *Annals of Forest Science* 77 (2): 35.

Elith, J., J. R. Leathwick, and T. Hastie. 2008. A Working Guide to Boosted Regression Trees. *Journal of Animal Ecology*.

Elith, Jane, and John Leathwick. 2015. Boosted Regression Trees for Ecological Modeling, 1–22.

Englin, J., J. Loomis, and A. González-Cabán. 2001. The Dynamic Path of Recreational Values Following a Forest Fire: A Comparative Analysis of States in the Intermountain West. *Canadian Journal of Forest Research* 31 (10): 1837–44.

Fargeon, H, F. Pimont, N. Martin-StPaul, M. De Caceres, J Ruffault, R. Barbero, and J. L. Dupuy. 2020. Projections of Fire Danger under Climate Change over France: Where Do the Greatest Uncertainties Lie? *Climatic Change* 160 (3): 479–93.

Fargeon, Hélène. 2019. Effet Du Changement Climatique Sur l'évolution de l'aléa Incendie de Forêt En France Métropolitaine Au 21ème Siècle.

Faustmann, Martin. 1849. Berechnung Des Wertes Welchen Wladboden Sowie Noch Nicht Haubare Holzbestände Für Die Wladwirtschaft Besitzen [Calculation of the Value Which Forest Land and Immature Stands Possess for Forestry]. *Allgemeine Forst- Und Jadg-Zeitung* 15: 441–55.

Feld, Christian K, Pedro Segurado, and Cayetano Gutiérrez-Cánovas. 2016. Analysing the Impact of Multiple Stressors in Aquatic Biomonitoring Data: A "Cookbook" with Applications in R. *Science of the Total Environment* 573: 1320–39.

Fernandes, Paulo M., and Eric Rigolot. 2007. The Fire Ecology and Management of Maritime Pine (Pinus Pinaster Ait.). *Forest Ecology and Management* 241 (1–3): 1–13.

Fernandes, Paulo M., José A. Vega, Enrique Jiménez, and Eric Rigolot. 2008. Fire Resistance of European Pines. *Forest Ecology and Management*. Elsevier.

Finney, Mark A. 2005. The Challenge of Quantitative Risk Analysis for Wildland Fire. In *Forest Ecology and Management*, 211:97–108.

Flannigan, Mike D., Meg A. Krawchuk, William J. De Groot, B. Mike Wotton, and Lynn M. Gowman. 2009. Implications of Changing Climate for Global Wildland Fire. *International Journal of Wildland Fire*. CSIRO PUBLISHING.

Fréjaville, Thibaut, and Thomas Curt. 2015. Spatiotemporal Patterns of Changes in Fire Regime and Climate: Defining the Pyroclimates of South-Eastern France (Mediterranean Basin). *Climatic Change* 129 (1–2): 239–51.

———. 2017. Seasonal Changes in the Human Alteration of Fire Regimes beyond the Climate Forcing. *Environmental Research Letters* 12 (3).

Fréjaville, Thibaut, Thomas Curt, and Christopher Carcaillet. 2018. Higher Potential Fire Intensity at the Dry Range Margins of European Mountain Trees. *Journal of Biogeography* 45 (9): 2003–15.

Fréjaville, Thibaut, Albert Vilà-Cabrera, Thomas Curt, and Christopher Carcaillet. 2018. Aridity and Competition Drive Fire Resistance Trait Covariation in Mountain Trees. *Ecosphere* 9 (12).

Gallardo, Marta, Israel Gómez, Lara Vilar, Javier Martínez-Vega, and Maria Pilar Martín. 2016. Impacts of Future Land Use/Land Cover on Wildfire Occurrence in the Madrid Region (Spain). *Regional Environmental Change* 16 (4): 1047–61.

Ganteaume, Anne, Andrea Camia, Marielle Jappiot, Jesus San-Miguel-Ayanz, Marlène Long-Fournel, and Corinne Lampin. 2013. A Review of the Main Driving Factors of Forest Fire Ignition over Europe. *Environmental Management*. Springer.

Ganteaume, Anne, and Marielle Jappiot. 2013. What Causes Large Fires in Southern France. *Forest Ecology and Management* 294: 76–85.

Garcia-Gonzalo, J., S. Marques, J. G. Borges, B. Botequim, M. M. Oliveira, J. Tomé, and M. Tomé. 2011. A Three-Step Approach to Post-Fire Mortality Modelling in Maritime Pine (Pinus Pinaster Ait) Stands for Enhanced Forest Planning in Portugal. *Forestry* 84 (2): 197–206.

Giglio, Louis, James T. Randerson, and Guido R. Van Der Werf. 2013. Analysis of Daily, Monthly, and Annual Burned Area Using the Fourth-Generation Global Fire Emissions Database (GFED4). *Journal of Geophysical Research: Biogeosciences* 118 (1): 317–28.

Gill, A. Malcolm, Scott L. Stephens, and Geoffrey J. Cary. 2013. The Worldwide "Wildfire" Problem. *Ecological Applications* 23 (2): 438–54.

Giorgi, Filippo, and Piero Lionello. 2008. Climate Change Projections for the Mediterranean Region. *Global and Planetary Change* 63 (2–3): 90–104.

González-Olabarria, José Ramón, Blas Mola-Yudego, and Lluis Coll. 2015. Different Factors for Different Causes: Analysis of the Spatial Aggregations of Fire Ignitions in Catalonia (Spain). *Risk Analysis* 35 (7): 1197–1209.

Handmer, John, and Robyn Betts. 2013. Estimating the Economic, Social and Environmental Impacts of Wildfires in Australia Catherine Stephenson1. *Environmental Hazards* 12 (2): 93–111.

Hantson, Stijn, Almut Arneth, Sandy P. Harrison, Douglas I. Kelley, I. Colin Prentice, Sam S. Rabin, Sally Archibald, et al. 2016. The Status and Challenge of Global Fire Modelling. *Biogeosciences* 13 (11): 3359–75.

Hardy, Colin C. 2005. Wildland Fire Hazard and Risk: Problems, Definitions, and Context. In *Forest Ecology and Management*, 211:73–82. Elsevier.

Hawkins, Ed, and Rowan Sutton. 2009. The Potential to Narrow Uncertainty in Regional Climate Predictions. *Bulletin of the American Meteorological Society* 90 (8): 1095–1107.

Hijmans, Robert J, Steven Phillips, John Leathwick, and Jane Elith Maintainer. 2017. Package "dismo" Type Package Title Species Distribution Modeling.

Hood, Sharon M., Charles W. McHugh, Kevin C. Ryan, Elizabeth Reinhardt, and Sheri L. Smith. 2007. Evaluation of a Post-Fire Tree Mortality Model for Western USA Conifers. *International Journal of Wildland Fire* 16 (6): 679–89.

Hood, Sharon M., J. Morgan Varner, Phillip Van Mantgem, and C. Alina Cansler. 2018. Fire and Tree Death: Understanding and Improving Modeling of Fire-Induced Tree Mortality. *Environmental Research Letters*.

Intergovernmental Panel on Climate Change. 2014. *Climate Change 2014 Synthesis Report - IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Gian-Kasper Plattner.

Jin, Yufang, Michael L. Goulden, Nicolas Faivre, Sander Veraverbeke, Fengpeng Sun, Alex Hall, Michael S. Hand, Simon Hook, and James T. Randerson. 2015. Identification of Two Distinct Fire Regimes in Southern California: Implications for Economic Impact and Future Change. *Environmental Research Letters* 10 (9).

Jolly, W. Matt, Mark A. Cochrane, Patrick H. Freeborn, Zachary A. Holden, Timothy J. Brown, Grant J. Williamson, and David M.J.S. Bowman. 2015. Climate-Induced Variations in Global Wildfire Danger from 1979 to 2013. *Nature Communications* 6 (July).

Kalabokidis, Kostas D, Nikos Koutsias, Pavlos Konstantinidis, and Christos Vasilakos. 2007. Multivariate Analysis of Landscape Wildfire Dynamics in a Mediterranean Ecosystem of Greece. *Area* 39 (3): 392–402.

Kallio, A. Maarit I. 2010. Accounting for Uncertainty in a Forest Sector Model Using Monte Carlo Simulation. *Forest Policy and Economics* 12 (1): 9–16.

Keeley, Jon E. 2012. Ecology and Evolution of Pine Life Histories. *Annals of Forest Science*.

Kloster, S., N. M. Mahowald, J. T. Randerson, P. E. Thornton, F. M. Hoffman, S. Levis, P. J. Lawrence, J. J. Feddema, K. W. Oleson, and D. M. Lawrence. 2010. Fire Dynamics during the 20th Century Simulated by the Community Land Model. *Biogeosciences* 7 (6): 1877–1902.

Kochi, Ikuho, Geoffrey H. Donovan, Patricia A. Champ, and John B. Loomis. 2010. The Economic Cost of Adverse Health Effectsfrom Wildfire-Smoke Exposure: A Review. *International Journal of Wildland Fire*. CSIRO PUBLISHING.

Kovats, Sari, Riccardo Valentini, Laurens M. Bouwer, Elena Georgopoulou, Daniela Jacob, Eric Martin, Mark Rounsevell, and Jean Francois Soussana. 2014. Europe. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by and L.L. White (eds.) Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, 1267–1326. Cambridge: Cambridge University Press.

Latta, Gregory S., Hanne K. Sjolie, and Birger Solberg. 2013. A Review of Recent Developments and Applications of Partial Equilibrium Models of the Forest Sector. *Journal of Forest Economics* 19 (4): 350–60.

Lehner, Flavio, Clara Deser, Nicola Maher, Jochem Marotzke, Erich M Fischer, Lukas Brunner, Reto Knutti, and Ed Hawkins. 2020. Partitioning Climate Projection Uncertainty with Multiple Large Ensembles and CMIP5/6. *Earth System Dynamics* 11 (2): 491–508.

Li, F, X D Zeng, and S Levis. 2012. A Process-Based Fire Parameterization of Intermediate Complexity in a Dynamic Global Vegetation Model. *Biogeosciences* 9 (7): 2761–80.

Lindgren, Finn, and Håvard Rue. 2015. Bayesian Spatial Modelling with R-INLA. *Journal of Statistical Software* 63 (19): 1–25.

Lindner, Marcus, Michael Maroschek, Sigrid Netherer, Antoine Kremer, Anna Barbati, Jordi Garcia-Gonzalo, Rupert Seidl, et al. 2010. Climate Change Impacts, Adaptive Capacity, and Vulnerability of European Forest Ecosystems. *Forest Ecology and Management* 259 (4): 698–709.

Liu, Yongqiang, Scott Goodrick, and Warren Heilman. 2014. Wildland Fire Emissions, Carbon, and Climate: Wildfire-Climate Interactions. *Forest Ecology and Management* 317 (April): 80–96.

Lobianco, Antonello, Philippe Delacote, Sylvain Caurla, and Ahmed Barkaoui. 2015. The Importance of Introducing Spatial Heterogeneity in Bio-Economic Forest Models: Insights Gleaned from FFSM++. *Ecological Modelling* 309–310: 82–92.

Mancini, Leone D., Piermaria Corona, and Luca Salvati. 2018. Ranking the Importance of Wildfires' Human Drivers through a Multi-Model Regression Approach. *Environmental Impact Assessment Review* 72 (January): 177–86.

Mann, Michael E. 2008. Smoothing of Climate Time Series Revisited. *Geophysical Research Letters* 35 (16).

Maringer, Janet, Davide Ascoli, Nicolas Küffer, Sebastian Schmidtlein, and Marco Conedera. 2016. What Drives European Beech (Fagus Sylvatica L.) Mortality after Forest Fires of Varying Severity? *Forest Ecology and Management* 368: 81–93.

Miller, Carol, and Alan A Ager. 2013. A Review of Recent Advances in Risk Analysis for Wildfire Management. *International Journal of Wildland Fire*.

Moigne, P Le. 2002. Description de l'analyse Des Champs de Surface Sur La France Par Le Système Safran. *Note de Centre GMME, Météo-France*.

Molina Martínez, Juan Ramón, Miguel Herrera Machuca, Ricardo Zamora Díaz, Francisco Rodríguez y Silva, and Armando González-Cabán. 2011. Economic Losses to Iberian Swine Production from Forest Fires. *Forest Policy and Economics* 13 (8): 614–21.

Moreira, Francisco, Olga Viedma, Margarita Arianoutsou, Thomas Curt, Nikos Koutsias, Eric Rigolot, Anna Barbati, et al. 2011. Landscape - Wildfire Interactions in Southern Europe: Implications for Landscape Management. *Journal of Environmental Management*. Academic Press.

Nunes, A. N., L. Lourenço, and A. C.Castro Meira. 2016. Exploring Spatial Patterns and Drivers of Forest Fires in Portugal (1980–2014). *Science of the Total Environment* 573: 1190–1202.

O'Brien, J. J., J. K. Hiers, J. M. Varner, C. M. Hoffman, M. B. Dickinson, S. T. Michaletz, E. L. Loudermilk, and B. W. Butler. 2018. Advances in Mechanistic Approaches to Quantifying Biophysical Fire Effects. *Current Forestry Reports*. Springer International Publishing.

Oliveira, Sandra, Friderike Oehler, Jesús San-Miguel-Ayanz, Andrea Camia, and José M.C. Pereira. 2012. Modeling Spatial Patterns of Fire Occurrence in Mediterranean Europe Using Multiple Regression and Random Forest. *Forest Ecology and Management* 275 (July): 117–29.

Opitz, Thomas, Florent Bonneu, and Edith Gabriel. 2020. Point-Process Based Bayesian Modeling of Space–Time Structures of Forest Fire Occurrences in Mediterranean France. *Spatial Statistics*.

Page, Y. Le, G. Hurtt, A. M. Thomson, B. Bond-Lamberty, P. Patel, M. Wise, K. Calvin, et al. 2013. Sensitivity of Climate Mitigation Strategies to Natural Disturbances. *Environmental Research Letters* 8 (1).

Papakosta, Panagiota, and Daniel Straub. 2017. Probabilistic Prediction of Daily Fire Occurrence in the Mediterranean with Readily Available Spatio-Temporal Data. *IForest* 10 (1): 32–40.

Pausas, Juli G, and Jon E Keeley. 2019. Wildfires as an Ecosystem Service. *Frontiers in Ecology and the Environment* 17 (5): 289–95.

Petucco, Claudio, Antonello Lobianco, and Sylvain Caurla. 2019. Economic Evaluation of an Invasive Forest Pathogen at a

Large Scale: The Case of Ash Dieback in France. *Environmental Modeling and Assessment*.
Pimont, François, Jean-luc Dupuy, Eric Rigolot, and Yvon Duché. 2014. Les Effets Du Passage d'un Feu Dans Un Peuplement Arboré. Synthèse Des Connaissances et Applications Pour Le Gestionnaire Forestier Méditerranéen. *Forêt Méditerranéenne* XXXV (1): 17–30.
Pimont F., Fargeon H., Opitz T., Ruffault J., Barbero R., Martin StPaul N., Rigolot E., Riviere M., Dupuy JL., in print. Prediction of regional wildfire activity in the probabilistic Bayesian framework of Firelihood. Ecological Applications.
Pimont, François, Russell Parsons, Eric Rigolot, François de Coligny, Jean Luc Dupuy, Philippe Dreyfus, and Rodman R. Linn. 2016. Modeling Fuels and Fire Effects in 3D: Model Description and Applications. *Environmental Modelling and Software* 80 (June): 225–44.
Pimont, François, Roger Prodon, and Eric Rigolot. 2011. Comparison of Postfire Mortality in Endemic Corsican Black Pine (Pinus Nigra Ssp. Laricio) and Its Direct Competitor (Pinus Pinaster). *Annals of Forest Science* 68 (2): 425–32.
Preisler, Haiganoush K., and Alan A. Ager. 2013. Forest-Fire ModelsBased in Part on the Article "Forest Fire Models" by Haiganoush K. Preisler and David R. Weise, Which Appeared in the Encyclopedia of Environmetrics . In *Encyclopedia of Environmetrics*.
Prestemon, Jeffrey P., Karen L Abt, and Robert J Huggett. 2008. Market Impacts of a Multiyear Mechanical Fuel Treatment Program in the U.S. *Forest Policy and Economics* 10 (6): 386–99.
Prestemon, Jeffrey P, Karen L Abt, Kevin M Potter, and Frank H Koch. 2013. An Economic Assessment of Mountain Pine Beetle Timber Salvage in the West. *Western Journal of Applied Forestry* 28 (4): 143–53.
Prieg, Lydia, and Dmitry Yumashev. 2020. Frameworks for Dealing with Climate and Economic Uncertainties in Integrated Assessment Models. *Integrated Assessment Models and Others Climate Policy Tools*, no. June.
QGIS.org. 2020. QGIS Geographic Information System. Open Source Geospatial Foundation.
Quinet, Alain. 2019. La Valeur de l'action Pour Le Climat Une Valeur Tutélaire Du Carbone Pour Évaluer Les Investissements et Les Politiques Publiques Rapport de La Commission Présidée Par.
Reed, William J. 1984. The Effects of the Risk of Fire on the Optimal Rotation of a Forest. *Journal of Environmental Economics and Management* 11 (2): 180–90.
Reyer, Christopher, Petra Lasch-Born, Felicitas Suckow, Martin Gutsch, Aline Murawski, and Tobias Pilz. 2014. Projections of Regional Changes in Forest Net Primary Productivity for Different Tree Species in Europe Driven by Climate Change and Carbon Dioxide. *Annals of Forest Science* 71 (2): 211–25.
Reyer, Christopher P.O., Stephen Bathgate, Kristina Blennow, Jose G. Borges, Harald Bugmann, Sylvain Delzon, Sonia P. Faias, et al. 2017. Are Forest Disturbances Amplifying or Canceling out Climate Change-Induced Productivity Changes in European Forests? *Environmental Research Letters* 12 (3).
Rigolot, Eric. 2004. Predicting Postfire Mortality of Pinus Halepensis Mill. and Pinus Pinea L. *Plant Ecology* 171 (1–2): 139–51.
Riviere, Miguel, Sylvain Caurla, and Philippe Delacote. 2020. Evolving Integrated Models From Narrower Economic Tools: The Example of Forest Sector Models. *Environmental Modeling & Assessment* In Press (March): 1–17.
Rodrigues, M., J. de la Riva, and S. Fotheringham. 2014. Modeling the Spatial Variation of the Explanatory Factors of Human-Caused Wildfires in Spain Using Geographically Weightedlogistic Regression. *Applied Geography* 48: 52–63.
Rodrigues, Marcos, and Juan De la Riva. 2014. An Insight into Machine-Learning Algorithms to Model Human-Caused Wildfire Occurrence. *Environmental Modelling and Software* 57 (July): 192–201.
Rothermel, R C. 1972. *A Mathematical Model for Predicting Fire Spread in Wildland Fuels*.
Rue, Håvard, Sara Martino, and Nicolas Chopin. 2009. Approximate Bayesian Inference for Latent Gaussian Models by Using Integrated Nested Laplace Approximations. *Journal of the Royal Statistical Society. Series B: Statistical Methodology* 71 (2): 319–92.
Ruffault, J., F. Mouillot, and D. P.C. Peters. 2015. How a New Fire-Suppression Policy Can Abruptly Reshape the Fire-Weather Relationship. *Ecosphere* 6 (10): art199.
Ruffault, Julien, Nicolas K. Martin-StPaul, Serge Rambal, and Florent Mouillot. 2013. Differential Regional Responses in Drought Length, Intensity and Timing to Recent Climate Changes in a Mediterranean Forested Ecosystem. *Climatic Change* 117 (1–2): 103–17.
Ruffault, Julien, and Florent Mouillot. 2017. Contribution of Human and Biophysical Factors to the Spatial Distribution of Forest Fire Ignitions and Large Wildfires in a French Mediterranean Region. *International Journal of Wildland Fire* 26 (6): 498–508.
Ryan, KC, and GD Amman. 1994. Interactions between Fire-Injured Trees and Insects in the Greater Yellowstone Area. *Plants and Their Environments : Proceedings of the First Biennial Scientific Conference on the Greater Yellowstone Ecosystem*, 259–71.
San-Miguel-Ayanz, J, T Durrant, R Boca, and G Libertà. 2019. Forest Fires in Europe, Middle East and North Africa 2018.
Schelhaas, M. J., G. J. Nabuurs, M. Sonntag, and A. Pussinen. 2002. Adding Natural Disturbances to a Large-Scale Forest Scenario Model and a Case Study for Switzerland. *Forest Ecology and Management* 167 (1–3): 13–26.
Scott, Joe H. 2006. An Analytical Framework for Quantifying Wildland Fire Risk and Fuel Treatment Benefi T. *Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.*, 169–84.
Seidl, Rupert, Mart Jan Schelhaas, Marcus Lindner, and Manfred J. Lexer. 2009. Modelling Bark Beetle Disturbances in a Large Scale Forest Scenario Model to Assess Climate Change Impacts and Evaluate Adaptive Management Strategies. *Regional Environmental Change* 9 (2): 101–19.
Seidl, Rupert, Mart Jan Schelhaas, Werner Rammer, and Pieter Johannes Verkerk. 2014. Increasing Forest Disturbances in Europe and Their Impact on Carbon Storage. *Nature Climate Change* 4 (9): 806–10.
Seidl, Rupert, Dominik Thom, Markus Kautz, Dario Martin-Benito, Mikko Peltoniemi, Giorgio Vacchiano, Jan Wild, et al. 2017. Forest Disturbances under Climate Change. *Nature Climate Change*. Nature Publishing Group.

Sohngen, Brent L, and Richard W Haynes. 1997. The Potential for Increasing Carbon Storage in United States Unreserved Timberlands by Reducing Forest Fire Frequency: An Economic and Ecological Analysis. *Climatic Change* 35 (2): 179–97.

Taccoen, Adrien, Christian Piedallu, Ingrid Seynave, Vincent Perez, Anne Gégout-Petit, Louis Michel Nageleisen, Jean Daniel Bontemps, and Jean Claude Gégout. 2019. Background Mortality Drivers of European Tree Species: Climate Change Matters. *Proceedings of the Royal Society B: Biological Sciences* 286 (1900).

Taylor, S. W., Douglas G. Woolford, C. B. Dean, and David L. Martell. 2013. Wildfire Prediction to Inform Fire Management: Statistical Science Challenges. *Statistical Science* 28 (4): 586–615.

The Core Writing Team IPCC. 2015. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. *Ipcc*. Vol. 9. Copernicus GmbH.

Thonicke, K., S. Venevsky, S. Sitch, and W. Cramer. 2001. The Role of Fire Disturbance for Global Vegetation Dynamics: Coupling Fire into a Dynamic Global Vegetation Model. *Global Ecology and Biogeography* 10 (6): 661–77.

Thonicke, K, A Spessa, I C Prentice, S P Harrison, L Dong, and C Carmona-Moreno. 2010. The Influence of Vegetation, Fire Spread and Fire Behaviour on Biomass Burning and Trace Gas Emissions: Results from a Process-Based Model. *Biogeosciences* 7 (6): 1991–2011.

Vaillant, Nicole M., Crystal A. Kolden, and Alistair M.S. Smith. 2016. Assessing Landscape Vulnerability to Wildfire in the USA. *Current Forestry Reports*. Springer International Publishing.

Venevsky, Sergey, Yannick Le Page, José M.C. Pereira, and Chao Wu. 2019. Analysis Fire Patterns and Drivers with a Global SEVER-FIRE v1.0 Model Incorporated into Dynamic Global Vegetation Model and Satellite and on-Ground Observations. *Geoscientific Model Development* 12 (1): 89–110.

Verma, Satyam, and S Jayakumar. 2012. Impact of Forest Fire on Physical, Chemical and Biological Properties of Soil: A. *Proceedings of the International Academy of …* 2 (3): 168–76.

Vidal, Jean Philippe, Eric Martin, Laurent Franchistéguy, Martine Baillon, and Jean Michel Soubeyroux. 2010. A 50-Year High-Resolution Atmospheric Reanalysis over France with the Safran System. *International Journal of Climatology* 30 (11): 1627–44.

Vilar, Lara, Israel Gómez, Javier Martínez-Vega, Pilar Echavarría, David Riaño, and M. Pilar Martín. 2016. Multitemporal Modelling of Socio-Economic Wildfire Drivers in Central Spain between the 1980s and the 2000s: Comparing Generalized Linear Models to Machine Learning Algorithms. *PLoS ONE* 11 (8): 1–17.

Wagner, C. E. Van. 1977. Conditions for the Start and Spread of Crown Fire. *Canadian Journal of Forest Research* 7 (1): 23–34.

Wagner, C. E. Van. 1987a. *Development and Structure of the Canadian Forest Fire Weather Index System*. *Forestry*.

———. 1987b. *Development and Structure of the Canadian Forest Fire Weather Index System*. *Forestry*. Vol. 51.

Wang, Xianli, B. Mike Wotton, Alan S. Cantin, Marc André Parisien, Kerry Anderson, Brett Moore, and Mike D. Flannigan. 2017. Cffdrs: An R Package for the Canadian Forest Fire Danger Rating System. *Ecological Processes* 6 (1).

Westerling, A. L., and B. P. Bryant. 2007. Climate Change and Wildfire in California. *Climatic Change* 87 (1 SUPPL): 231–49.

Westerling, A. L., B P Bryant, H K Preisler, T P Holmes, H G Hidalgo, T. Das, and S R Shrestha. 2011. Climate Change and Growth Scenarios for California Wildfire. *Climatic Change* 109 (SUPPL. 1): 445–63.

Woolley, Travis, David C. Shaw, Lisa M. Ganio, and Stephen Fitzgerald. 2012. A Review of Logistic Regression Models Used to Predict Post-Fire Tree Mortality of Western North American Conifers. *International Journal of Wildland Fire*.

Xi, Dexen D.Z., Stephen W. Taylor, Douglas G. Woolford, and C.B. Dean. 2019. Statistical Models of Key Components of Wildfire Risk. *Annual Review of Statistics and Its Application* 6 (1): 197–222.

Conclusion

Main results, contributions, and avenues for future research

Conclusion

1. Summary of the main results

Forestry and the forest sector have the ability to provide multiple goods and services beyond timber production. The forest sector is consequently increasingly leveraged by forest-related policy to address environmental challenges in the fields of e.g. climate, renewable energy, and biodiversity conservation. Forest Sector Models (FSMs) are numerical simulation models of the forest sector developed in the 1970s for prospective analysis related to forest resources and timber markets. In the light of recent policy trends, the general aim of this thesis was to explore FSMs' ability to provide valuable insights to forest policy-making in the context of this transition towards wider environmental questions.

We first performed a parallel exploration of the FSM literature in the last 50 years on the one hand, and of the literature in the history and epistemology of model-based research in economics on the other, with the objective of shedding light on the mechanisms through which FSM research is able to support policymaking (chapter 1). Having highlighted the main connections between FSMs and forest policy, we subsequently focused on the ability of FSM research to address issues other than timber production and wood products markets, which we documented via quantitative and narrative reviews of the more recent literature (chapter 2). With the basis laid for a good understanding of FSMs' ability to contribute to environmental policy from a conceptual perspective, we later turned to performing applied analyses focused on climate change mitigation and adaptation in the French forest sector. Using the French Forest Sector Model (FFSM), we first investigated the implications for forestry and forest landscapes of management practices aiming at *in situ* carbon sequestration (chapter 3). Then, we explored the consequences for the forest sector of climate-induced changes in wildfire regimes while also assessing the propagation of several sources of climate-induced uncertainties in model projections (chapter 4).

FSM are able to inform policymaking by representing their target –the forest sector- and allowing modelers to draw conclusions about it through "surrogative reasoning", i.e. experimenting on the model's representation of the forest sector to answer questions about the real world. Forest policy has strong historical ties to FSM development, which can be witnessed in the early and continued use of FSMs in outlook studies for the forest sector. As a result, policy agendas influence model use in several ways, including (1) the choice of facts to be represented, (2) the questions to be addressed and (3) the content of narratives and scenarios used to drive model simulations and tie results to the real world. Besides, owing to the strong diversity in natural and economic contexts worldwide, policy agendas shift across regions, which reflects in model building and model use (chapter 1). The investigation of non-timber objectives in FSM research (chapter 2) constitutes a good illustration of these trends. Over the last decades, forest policy centred itself on environmental concerns and their articulation with traditional economic objectives, and so did FSM research. In the 1990s, a majority of articles published concerned solely timber production or trade while, on the contrary, since 2010 more than half had an objective other than the production of timber as a core focus. These include the production of renewable energy, climate change mitigation and impacts, biodiversity and habitat conservation, the regulation of disturbances, and that of water services.

However, policy is not the only determinant of model-based research. Other important factors include the nature of facts represented (ecological, technological, behaviours), the local context, the availability of data as well as past theoretical and methodological developments. Their influence can be witnessed in the methods and theories chosen for representation as well as in the structuration of the research field along geographical and methodological boundaries (chapter 1). Once again, this can be illustrated in contemporary FSM research by focusing on the introduction of non-timber objectives into FSM, which has been incomplete and unequal (chapter 2). On the one hand, objectives with direct ties to FSMs' original target such as energy production (to market dynamics) and carbon storage (to forest resource modelling) have been more often treated and their inclusion as decision variables has required limited amounts of changes to be made to the models. On the other hand, objectives related to cultural and many regulation services have been, as in the more general literature, less often treated, often modelled with proxies, or implicitly considered through their (usually negative) implications for timber production. Reasons for this include difficulties in estimating their economic value for inclusion if FSMs' objective function – an economic surplus -, the unavailability of empirical data or the large-scale nature of models, which makes them unable to incorporate data at fine spatial scales.

In recent years, modelling turned to two strategies to address such challenges: (a) the development of models at the local to regional scales and to (b) the use of multi-model environments through model couplings. Both solutions contribute to expanding the target system's boundaries and allowing for the incorporation of new facts into FSM, thus widening the range of possible questions to be addressed. However, they increase model complexity and often require researchers to perform inter-disciplinary research (chapters 1-2).

In chapter 3, we leveraged strategy (a) by employing a spatially-disaggregated model of the French forest sector embedded with Hartman's (1976) model for optimal rotations with non-timber amenities to investigate the implications of management practices aiming at both sequestering carbon and producing timber. While simulations predictably showed that taking into account sequestration benefits in management decisions resulted in increases in forest carbon, being able to simulate multiple decisions across heterogeneous environmental conditions at the individual owner scale enabled us to pinpoint several facts. First, while the postponing of harvests is the main lever to store carbon in the short term, changing species composition and management regimes provides additional benefits in the long term. Second, such changes have implications for forest landscapes, which comprise a larger share of mixed and broadleaf forests, but also of larger trees, by the end of the century. While such an evolution may provide co-benefits (e.g. biodiversity, aesthetic amenities), it could also be at odds with policy objectives that seek to increase harvests. Third, local conditions are indeed important, and potentials to store additional carbon varies both across and within regions, stressing the importance of considering heterogeneity in environmental conditions in large-scale assessments. Fourth, some southern regions with relatively slow growth dynamics, already long rotations and high exposure to disturbances may not be well suited to sequestration objectives.

This latter point was the focus of chapter 4, where we leveraged strategy (b) and used a probabilistic model of fire activity together with the FFSM, for which we developed a fire effects module, to investigate implications for the forest sector of climate-induced changes in wildfire regimes, and for model forecasts of uncertainties associated to these changes. Even though wildfires are locally significant and burned areas are expected to increase significantly, impacts on the forest sector - losses of timber resources and carbon, decreases in harvests and price increases, especially for softwoods – remain limited to a few percentages points at the sectoral scale. Fires affect a limited amount of resources every year, but in a quasi-cumulative manner, and differences across scenarios are mostly witnessed in the latter half of the century. In a context where climate policy often makes strong assumptions on the forest sector's ability to compensate residual emissions to reach carbon neutrality objectives, these impacts remain relevant, especially given that fires may interact with other risks of catastrophic and background forest mortality. Contrary to climate and fire dynamics, forecasts for forest sector dynamics show low levels of uncertainty at first, which surge over a few decades. On the one hand, inter-annual fluctuations in fire activity only marginally propagate to the forest sector, and most of the uncertainty comes from the choice of a climate model and that of a forcing level, especially in the long-term. On the other hand, uncertainty due to stochasticity in the wildfire phenomenon, even though it is never predominant, accounts for a sizeable and stable proportion of total uncertainty throughout simulations. While these results are partly dependent on modelling hypotheses, (1) they confirm the importance of considering several possible outlooks for climate change when making long-term simulations, and (2) they stress the importance of taking into account the inherent variability in disturbance processes - and more generally environmental processes – in large-scale forest modelling.

2. Main contributions

2.1. Contributions to forest sector modelling

Within the field of Forest Sector Modelling, this thesis first brings a conceptual contribution by linking past and present FSM research to the literature in the epistemology and history of model-based research and drawing parallels to other fields, thus laying the basis for further discussions on the relationships between models, policy and the real-world forest sector. In this sense, it constitutes a continuation of previous works focused on historical model development (Adams and Haynes 2007; Buongiorno 1996; Latta, Sjolie, and Solberg 2013), comparing modelling paradigms (Sjølie et al. 2015; Sohngen et al. 1997), and using models for policy analysis (Hurmekoski and Hetemäki 2013; Solberg 1986; Toppinen and Kuuluvainen 2010).

Second, this thesis focuses on the specific issue of environmental stakes in the forest sector through the lens of non-timber management objectives, their implications for landscapes, and their ability to contribute to climate change mitigation and adaptation. Therefore, it also brings a thematic contribution to the field by objectivizing its recent shift towards such "upstream" questions and subsequently exploring some of them. This exploration is focused on France, a study case made relevant by the strong heterogeneity in environmental conditions throughout the country. The local environmental context is often overlooked in large-scale model-based research, especially when they focus on industries and markets downstream, hence this specificity contributes to shedding light on the importance of their consideration by sectoral studies.

Third, this thesis brings methodological contributions. A first methodological contribution is found in the use of a spatially-explicit and multi-scale model for the exploration of the factors mentioned above, i.e. local environmental conditions as determinants of non-timber dynamics - carbon storage & disturbances - at the sectoral scale. Second, by assessing the propagation of different sources of uncertainty in simulation results and introducing a stochastic model component, this work confirms the importance of considering multiple possible outlooks in forecasts and contributes to the discussion on the inclusion of risk and uncertainties in sectoral models, previously identified as a key limitation in the field (Chudy, Sjølie, and Solberg 2016). More generally, this thesis integrates spatial price equilibrium and resource modelling techniques found in traditional FSM research together with other modelling paradigms from the broader environmental sciences, e.g. Hartman's (1976) optimal rotation model, probabilistic fire modelling, machine learning, Global Circulation Models. By doing so, this thesis contributes to bridging the gap between forest sector modelling and other fields and disciplines.

2.2. Contributions to the laboratory's research project

As explained previously, this thesis takes place within the FFSM research project at the BETA laboratory, and more generally forms part of the laboratory's research programme on forest management and forest economics.

With regards to the FFSM project, this thesis, through its conceptual dimensions, first contributes to making a synthesis of research performed by the team over the past 10 years, to replacing it within FSM research worldwide and to identifying its contributions to the field. Second, through the methods used, it contributes to leveraging recent model developments in downscaling the model and improving the representation of forest resources and management (Lobianco et al. 2016). It also furthers the team's aim of using the FFSM together with other modelling frameworks (Beaussier 2020; Caurla et al. 2018; Delacote et al., in print.; Lenglet, Courtonne, and Caurla 2017), strengthening its position as a resolutely multi-disciplinary forest modelling research unit. Third, through its thematic foci, this thesis expands previous work on (1) climate change mitigation, up to now largely focused on renewable energy production (e.g. Caurla et al. 2013, 2018), and on (2) climate change adaptation, which used to be a minor focus and had to this day addressed storms and pests (Caurla, Garcia, and Niedzwiedz 2015; Petucco, Lobianco, and Caurla 2019), but not wildfires.

Even though not an objective in itself in the first place, retrospectively, this thesis has also contributed to bridging the gap between the FFSM project and research performed in other projects at BETA. These include links to research on forest economics and modelling at the stand scale, forest management with carbon benefits, and the adaptation of management practices to disturbance risks (e.g. Brèteau-Amores et al. 2020; Brèteau-Amores, Brunette, and Davi 2019; Brunette, Couture, and Laye 2015; Petucco and Andrés-Domenech 2018).

2.3. Personal contributions

Finally, my work has contributed to my personal development as a young scientist, in several ways. My academic background prior to this thesis was in the general natural sciences and in forestry. The work I performed at BETA therefore constituted my first true foray into economics via the particular field of forest economics. In particular, chapter 1 (and chapter 2 to a lesser degree) required me to develop a broader understanding of forest sector modelling, forest economics and model-based applied economics in general. As a result, this thesis has contributed to widening my perspectives on a topic I was already familiar with, forests and forestry, through a new discipline. Its content, which I believe to be a good synthesis of my previous background, my more recent orientations and my taste for modelling approaches, consequently strengthened my ability to perform forest-centred multi-disciplinary research. It also confirmed my will to continue down this path, as I believe such profiles to be useful in research, which is often structured along disciplinary axes.

This thesis has also influenced my way of working. As for many other PhD students, it helped me develop critical thinking, scientific rigor, as well as skills in writing, planning and communication. On several occasions, it also made me realise that, in research, everything takes longer than expected: retrospectively, one of this thesis' major personal contributions was therefore to help me develop (some) patience. More importantly, it taught me to work independently and collectively at the same time. Indeed, while I was on the one hand gradually becoming more independent from my supervisors, I had on the other hand to develop collaborations with other scientists in order to address the more delicate aspects of my research. Chapter 4 was in that sense significant, and the establishment of a collaboration with co-authors at INRAE in Avignon constituted a personal (fruitful!) challenge.

Finally, this thesis was financed by the French Ministry of Agriculture within a framework for the doctoral training of civil servants. My doctoral training has therefore provided me with some keys to help bridge the gap between science and policy making, and, perhaps more importantly, between researchers and policy officers. Even though I wish as of today to continue working for some time in research at the interface with policy, whatever my future career will be, such skills should prove useful, and I hope will help me develop mutual understanding at this crucial interface.

3. Future research

In addition to the limitations discussed in individual chapters, I want to highlight three additional broader boundaries of my work and the perspectives they offer for further research. These relate to (1) adopting a multi-sectoral approach, (2) addressing issues beyond the sectoral scale and with other methods than forest sector models, and (3) furthering research on model robustness.

(1) This thesis focused solely on the forest sector, and the model used for study cases considers land-use changes as an exogenous variable. Forest area is increasing in France in several regions, afforestation is often singled out as a lever to increase carbon sequestration, and land-use change at the margins with agricultural and urban areas are important local drivers for the forest sector (Haim, White, and Alig 2015; Latta et al. 2016). Future research should focus on these aspects. While chapter 3 constituted a thought experiment and shed light on some of the spatial determinants of sequestration possibilities, a future objective will be to envision realistic incentives, possibly regionalised, with an explicit representation of interactions with agriculture. The usefulness of model couplings to overcome modelling obstacles has been illustrated on several occasions: a coupling with a model of the agricultural sector would likely help in simulating interactions. I am starting a new position at CIRED, a research laboratory where such agricultural models are being developed (e.g. Prudhomme et al. 2020), and I hope to be instrumental in developing collaborations with BETA. I will also continue investigating the land-use and socio-economic determinants of fire activity at the local to regional

scales in close collaboration with co-authors at INRAE in Avignon, starting with the co-direction of a master thesis on the topic.

(2) My work has addressed questions at the sectoral scale and was dedicated to using and improving forest sector models, even though other tools were also used. As stated in the introduction, given the many limitations of FSMs, it is important to consider results obtained with other research methods on the same topics. In the future, even though I will continue working with FSMs, I will also seek to use different methodologies, in particular at more local scales, hoping to get insight into some of the spatial trends emerging at larger scales with the FFSM. Regarding carbon dynamics, projects underway include the investigation of realistic silvicultural treatments for climate-smart forestry at the scale of the forest stand, using couplings between classical forest economics rotation models and detailed, process-based models of forest growth and carbon soil cycles. The inclusion into the FFSM of forest growth responses to climate change derived from process-based models is another project I have in mind. Regarding forest fires, my work has mostly concerned fire hazard. Using approaches based in physical geography and the concept of vulnerability, I wish to investigate the vulnerability of ecosystems and infrastructure to wildfires at the territorial scale. I am proposing with collaborators a master thesis on this topic, where a secondary objective will be the co-construction of vulnerability indices with local stakeholders. This also contributes to my will of integrating dimensions pertaining to other disciplines, here through mapping and participative approaches.

(3) FSMs, like other technico-economic models of the agricultural or energy sectors, are large models used for numerical simulation. Model robustness can be affected in several places - initial conditions, model parameters, exogenous parameters (scenarios) – and the models' size and computational complexity often preclude using systematic robustness analysis methods (Chudy, Sjølie, and Solberg 2016). In this thesis, I have treated one aspect: that of climate-driven uncertainties in the modelling of an ecological process. Model validation refers to verifying whether a model performs as intended or not. In the case of FSMs, it can be understood as making sure that simulation outputs conform to observations from the real-world. The FFSM model has now been used for more than 10 years: enough data is available to re-investigate this issue, and recent evidence from a master thesis highlight that, for instance, simulated trade flows do not compare well to observed trade flows (Mathieu 2019). I wish to conduct a systematic sensitivity analysis of model parameters to elicit potential variables with a strong influence on forecasts as a first step towards improving model robustness, with the objective to discriminate unimportant variables from important ones. A more ambitious goal is to reformulate the way spatial trade is represented in the FFSM, and I will participate to a PhD thesis committee on this topic. Regarding uncertainties surrounding the impacts of climate change, a topic I am keen on investigating is that of multiple-risks and interactions between them (e.g. pests and wildfires). A collaboration is being set-up within the framework of a new PhD project at BETA to study multiple-risks with the FFSM.

References

Adams, Darius Mainard, and Richard W. Haynes. 2007. Resource and Market Projections for Forest Policy Development : Twenty-Five Years of Experience with the U.S. RPA Timber Assessment. Springer.

Beaussier, Thomas. 2020. "Évaluation Économique et Environnementale Du Développement Régional d'une Filière En Interaction Multi-Secteur et Multi-Échelle : Cas de La Filière Forêt-Bois Du Grand Est." UNIVERSITÉ DE LORRAINE.

Brèteau-Amores, Sandrine, Marielle Brunette, and Hendrik Davi. 2019. "An Economic Comparison of Adaptation Strategies Towards a Drought-Induced Risk of Forest Decline." Ecological Economics 164: 106294.

Brèteau-Amores, Sandrine, Rasoul Yousefpour, Marc Hanewinkel, and Mathieu Fortin. 2020. Composition Diversification vs. Structure Diversification: How to Conciliate Timber Production and Carbon Sequestration Objectives under Drought and Windstorm Risks in Forest Ecosystems.

Brunette, Marielle, Stéphane Couture, and Jacques Laye. 2015. "Optimising Forest Management under Storm Risk with a Markov Decision Process Model." Journal of Environmental Economics and Policy 4(2): 141–63.

Buongiorno, Joseph. 1996. "Forest Sector Modeling: A Synthesis of Econometrics, Mathematical Programming, and System Dynamics Methods." International Journal of Forecasting 12(3): 329–43.

Caurla, Sylvain, Vincent Bertrand, Philippe Delacote, and Elodie Le Cadre. 2018. "Heat or Power: How to Increase the Use of Energy Wood at the Lowest Cost?" Energy Economics 75: 85–103.

Caurla, Sylvain, Philippe Delacote, Franck Lecocq, and Ahmed Barkaoui. 2013. "Stimulating Fuelwood Consumption through Public Policies: An Assessment of Economic and Resource Impacts Based on the French Forest Sector Model." Energy Policy 63: 338–47.

Caurla, Sylvain, Serge Garcia, and Alexandra Niedzwiedz. 2015. "Store or Export? An Economic Evaluation of Financial Compensation to Forest Sector after Windstorm. The Case of Hurricane Klaus." Forest Policy and Economics 61: 30–38.

Chudy, Rafal P., Hanne K. Sjølie, and Birger Solberg. 2016. "Incorporating Risk in Forest Sector Modeling – State of the Art and Promising Paths for Future Research." Scandinavian Journal of Forest Research 31(7): 719–27.

Delacote, Philippe et al. "The Loop Effect : How Climate Change Impacts the Mitigation Potential of the French Forest Sector." Journal of Forest Economics: 1–64.

Haim, David, Eric M White, and Ralph J Alig. 2015. "Agriculture Afforestation for Carbon Sequestration under Carbon Markets in the United States: Leakage Behavior from Regional Allowance Programs." Applied Economic Perspectives and Policy 38(1): 132–51.

Hurmekoski, Elias, and Lauri Hetemäki. 2013. "Studying the Future of the Forest Sector: Review and Implications for Long-Term Outlook Studies." Forest Policy and Economics 34: 17–29.

Latta, Gregory S., Darius M. Adams, Kathleen P. Bell, and Jeffrey D. Kline. 2016. "Evaluating Land-Use and Private Forest Management Responses to a Potential Forest Carbon Offset Sales Program in Western Oregon (USA)." Forest Policy and Economics 65: 1–8.

Latta, Gregory S., Hanne K. Sjolie, and Birger Solberg. 2013. "A Review of Recent Developments and Applications of Partial Equilibrium Models of the Forest Sector." Journal of Forest Economics 19(4): 350–60.

Lenglet, Jonathan, Jean-Yves Courtonne, and Sylvain Caurla. 2017. "Material Flow Analysis of the Forest-Wood Supply Chain: A Consequential Approach for Log Export Policies in France." Journal of Cleaner Production 165: 1296–1305.

Lobianco, Antonello, Sylvain Caurla, Philippe Delacote, and Ahmed Barkaoui. 2016. "Carbon Mitigation Potential of the French Forest Sector under Threat of Combined Physical and Market Impacts Due to Climate Change." Journal of Forest Economics 23: 4–26.

Lobianco, Antonello, Philippe Delacote, Sylvain Caurla, and Ahmed Barkaoui. 2015. "The Importance of Introducing Spatial Heterogeneity in Bio-Economic Forest Models: Insights Gleaned from FFSM++." Ecological Modelling 309–310: 82–92.

———. 2016. "Accounting for Active Management and Risk Attitude in Forest Sector Models An Impact Study on French Forests." Environ Model Assess 21: 391–405.

Mathieu, Valentin. 2019. Master thesis "Forest Sector Modeling: A Critical Analysis from the Perspective of the Notions of Space, Place, and Scale." AgroParisTech.

Petucco, Claudio, and Pablo Andrés-Domenech. 2018. "Land Expectation Value and Optimal Rotation Age of Maritime Pine Plantations under Multiple Risks." Journal of Forest Economics 30: 58–70.

Petucco, Claudio, Antonello Lobianco, and Sylvain Caurla. 2019. "Economic Evaluation of an Invasive Forest Pathogen at a Large Scale: The Case of Ash Dieback in France." Environmental Modeling and Assessment.

Prudhomme, Rémi et al. 2020. "Combining Mitigation Strategies to Increase Co-Benefits for Biodiversity and Food Security." Environmental Research Letters 15(11): 114005.

Sjølie, Hanne K. et al. 2015. "An Assessment of Forest Sector Modeling Approaches: Conceptual Differences and Quantitative Comparison." Scandinavian Journal of Forest Research 30(1): 60–72.

Sohngen, Brent, Robert Mendelsohn, Roger Sedjo, and Kenneth Lyon. 1997. An Analysis of Global Timber Markets.

Solberg, Birger. 1986. "Forest Sector Simulation Models as Methodological Tools in Forest Policy Analysis (Norway)." Silva Fennica 20(4): 419–27.

Toppinen, Anne, and Jari Kuuluvainen. 2010. "Forest Sector Modelling in Europe-the State of the Art and Future Research Directions." Forest Policy and Economics 12(1): 2–8.

Appendices

1. Appendix A – Overview of the FFSM

The FFSM is a modular bio-economic numerical simulation model of metropolitan France's forest sector (Figure A.1.1). Elements represented are (1) forest resources, (2) wood products markets, (3) management decisions by forest owners and (4) carbon stocks and flows. Like many other forest sector models, the FFSM is a synthesis of mathematical programming, econometrics, activity analysis and systems dynamics approaches (Buongiorno, 1996). The model is dynamic and describes its target with a yearly recursion where new conditions are calculated from conditions in the previous year. Initial conditions are calibrated from national statistics and parameter values are calibrated from the literature, from expert knowledge, or chosen by the user. The model was first developed as FFSM 1.0 (GAMS software) with only elements (1) and (2) represented (Caurla *et al.*, 2010). Element (3) was subsequently added when the model was made spatially explicit at the scale of 8km pixels as FFSM ++ (C++ programming language, Lobianco *et al.*, 2016). Element (1) was updated at the same time (Lobianco *et al.*, 2015), and carbon accounting was eventually added (Lobianco *et al.*, 2016). In this appendix, we give an overview of the model using information from the referenced literature on the model's development. For more information, the reader is invited to refer to articles referenced, or to the website to browse the source code (www.ffsm-project.org).

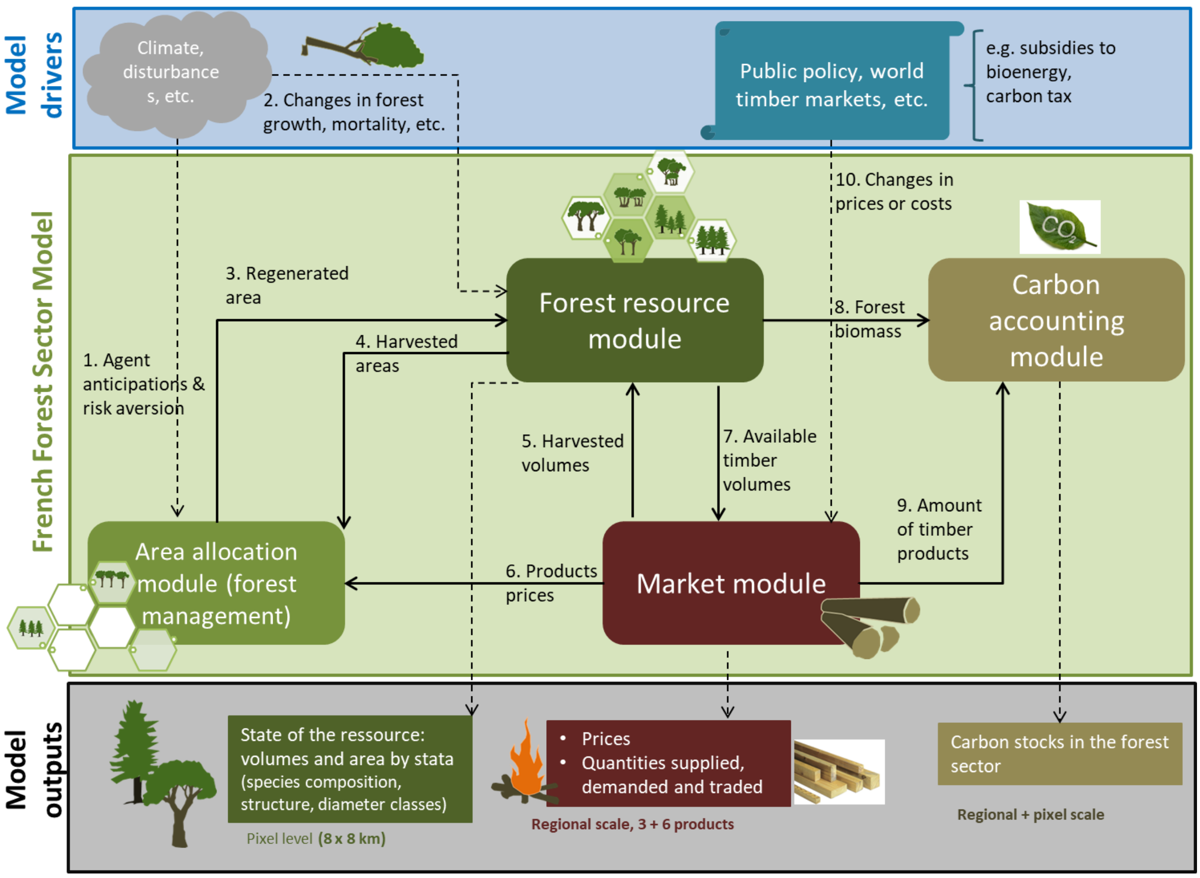


Figure A.1.1 – Overview of the FFSM model (reused and translated with authorization from S.Caurla).

A.1. FFSM market module

The market module represents the supply, demand, transformation and trade of 3 primary products and 6 transformed products across the model's 12 regions and one "rest of the world" region (Figure A.1.2). Timber supply is represented as a function of products prices and available timber inventories, and timber demand as a function of products prices. Products transformation is represented as a set of input-output processes with fixed coefficients. Domestic products are represented as imperfect substitutes to international products using Armington elasticities (Armington, 1969; Sauquet *et al.*, 2011). Equilibrium is found through Samuelson's spatial price equilibrium approach (Samuelson, 1952; Buongiorno, 1996), i.e. by solving a mathematical programming problem where net social surplus (the sum of producer and consumer surplus net of transportation costs) is maximized under a set of constraints ensuring yearly recursion, matter conservation and the non-negativity of key variables.

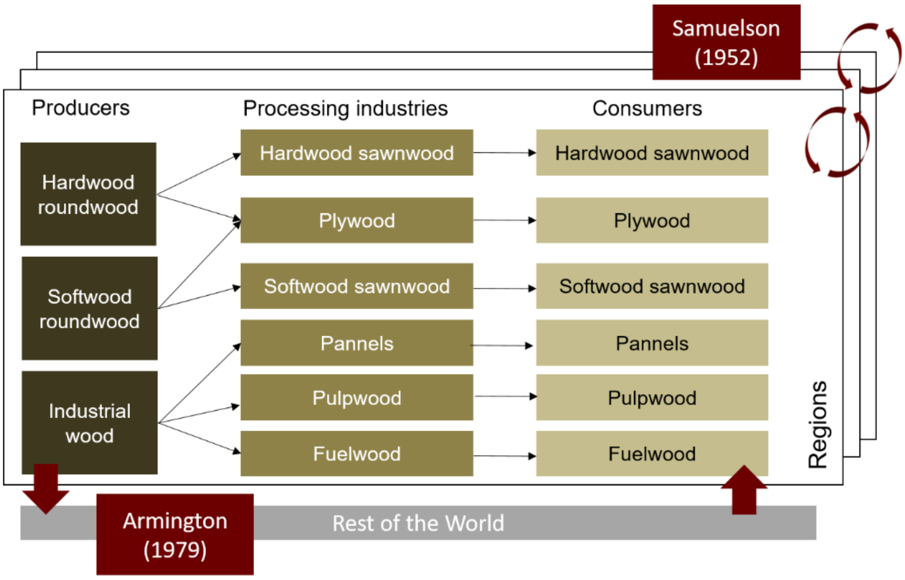


Figure A1.2 – Products, transformations and trade in the FFSM market module (reused with authorization from S.Caurla).

Following Caurla *et al.* (2010), net social surplus in the FFSM can be written as [A1.1][47]:

$$[A1.1] \quad NSS\left(\widetilde{P}_{p,i}, P_{p,i}, S_{p,i}, \widetilde{P}_{w,i}, P_{w,i}, S_{w,i}, D_{p,i}, e_{p,i,j}, e_{w,i,j}\right)$$
$$= \sum_{p,i}\left[\int_0^{D_{p,i}} \widetilde{P}_{p,i}(D)dD - \widetilde{P}_{p,i}D_{p,i}\right]$$
$$+ \sum_{w,i}\left[\widetilde{P}_{w,i}S_{w,i} - \int_0^{S_{w,i}} \widetilde{P}_{w,i}(S)dS\right]$$
$$+\sum_{p,i} S_{p,i}P_{p,i} - \sum_{p,i} c_p S_{p,i} + \sum_{w,i} D_{w,i}P_{w,i}$$
$$+\sum_{p,i,j}(P_{p,i} - P_{p,j} - C_{p,i,j})e_{p,i,j} + \sum_{w,i,j}(P_{w,i} - P_{w,j} - C_{w,i,j})e_{w,i,j}$$

where the first addend is equal to the surplus for consumers of transformed products p, the second addend to the surplus for producers of primary products w, addends 3 to 5 to the surplus for industries processing primary products into transformed products, and the last two addends to the surplus of transporters for both types of products across regions $\{i, j\}$.

[47] Market equilibrium is determined at the regional level in a given year. For readability, subscripts for years (t) have been omitted when not relevant.

Variables over which maximization is performed are products prices P, composite prices $\tilde{P}$ and quantities supplied S, demanded D and traded e. C and c respectively represent fixed processing and transport costs. NSS is then maximized under a set of constraints.

Demand and supply functions

The first set of constraints [A1.2-3] defines the supply S_w for composite primary products and the demand D_p for composite transformed products in year t and region i as functions of composite prices $\tilde{P}$, available timber inventories F and values of the previous year $t-1$.

$$[A1.2] \quad D_{p,i,t} = D_{p,i,t-1}\left(\frac{\widetilde{P}_{p,i,t}}{\widetilde{P}_{p,i,t-1}}\right)^{\varepsilon_p}$$

$$[A1.3] \quad S_{w,i,t} = S_{w,i,t-1}\left(\frac{\widetilde{P}_{w,i,t}}{\widetilde{P}_{w,i,t-1}}\right)^{\alpha_w}\left(\frac{F_{w,i,t}}{F_{w,i,t-1}}\right)^{\beta_w}$$

where ϵ, β and σ are price and inventory elasticities.

Transformation

Using fixed input-output coefficients a, the demand D_w for primary products is given as a linear combination of supplies S_p for transformed products [A1.4]. Besides, the supply of transformed products in a region is at maximum equal to processing capacities for processing industries K [A1.5].

$$[A1.4] \quad D_{w,i} = \sum_p a_{p,w} S_{p,i}$$

$$[A1.5] \quad S_{p,i} \leq K_{p,i}$$

Demand and supply within Armington's framework

Following Armington (1969), the demand for composite transformed products (p) is expressed as a function of demand for domestic products LD and demand for imported products M, with φ the elasticity of substitution between the two origins and b a constant representing the weight of each origin in the definition of composite products [A1.6].

$$[A1.6] \quad D_{p,i} = \left[(1-b_{D_{p,i}})LD_{p,i}^{\frac{\varphi_{p,i}-1}{\varphi_{p,i}}} + b_{D_{p,i}}M_{p,i}^{\frac{\varphi_{p,i}-1}{\varphi_{p,i}}}\right]^{\frac{\varphi_{p,i}}{\varphi_{p,i}-1}}$$

The demand for imported transformed products M is itself defined as a function of demand D for composite transformed products and of the ratio between composite prices $\tilde{P}$ and world prices P^* [A1.7].

$$[A1.7] \quad M_{p,i} = b_{D_{p,i}}^{\varphi_{p,i}} D_{p,i} \left(\frac{\widetilde{P}_{p,i}}{P_p^*} \right)^{\varphi_{p,i}}$$

And composite prices $\widetilde{P}$ are defined as a weighted average of local prices P and world prices P^* [A1.8].

$$[A1.8] \quad \widetilde{P}_{p,i} D_{p,i} = P_{p,i} LD_{p,i} + P_p^* M_{p,i}$$

Following the same pattern gives symmetric constraints for the supply of primary products w [A1.9-11].

$$[A1.9] \quad S_{w,i} = \left[(1 - b_{S_{w,i}}) LS_{w,i}^{\frac{\varphi_{w,i} - 1}{\varphi_{w,i}}} + b_{S_{p,i}} X_{w,i}^{\frac{\varphi_{w,i} - 1}{\varphi_{w,i}}} \right]^{\frac{\varphi_{w,i}}{\varphi_{w,i} - 1}}$$

$$[A1.10] \quad X_{w,i} = b_{S_{w,i}}^{\varphi_{w,i}} S_{w,i} \left(\frac{\widetilde{P}_{w,i}}{P_w^*} \right)^{\varphi_{w,i}}$$

$$[A1.11] \quad \widetilde{P}_{w,i} S_{w,i} = P_{w,i} LS_{w,i} + P_w^* X_{w,i}$$

Conservation of matter

Two constraints ensure the conservation of matter [A1.12-13]: for each region i, the supply of primary (w) or transformed (p) products plus all incoming trade fluxes from other regions j must be equal to all outgoing fluxes plus consumption of products within the region. For transformed products (p), consumption is expressed as the demand for domestic products (LD), while, for primary products *(w),* it is expressed as the sum of primary products used to manufacture transformed products.

$$[A1.12] \quad S_{p,i} + \sum_j e_{p,j,i} = LD_{p,i} + \sum_j e_{p,i,j}$$

$$[A1.13] \quad LS_{w,i} + \sum_j e_{w,j,i} = \sum_p a_{p,w} S_{p,i} + \sum_j e_{w,i,j}$$

Non-negativity

The last set of constraints ensures that quantities and prices are positive [A1.14-18]. They apply to traded quantities for primary and transformed products, prices for primary and transformed products, and to the supply of transformed products.

$$[A1.14] \quad e_{p,i,j} \geq 0$$

$$[A1.15] \quad e_{w,i,j} \geq 0$$

$$[A1.16] \quad P_{p,i} \geq 0$$

[A1.17] $P_{w,i} \geq 0$

[A1.18] $S_{p,i} \geq 0$

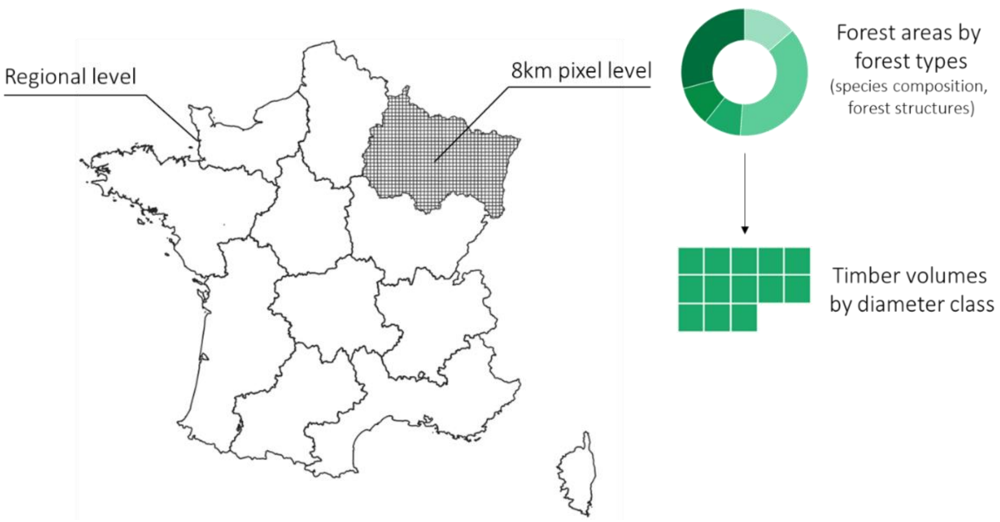
A.2. FFSM resource module

In the FFSM, forests are represented using a matrix-based approach where areas and volumes in several strata are tracked over time (Caurla *et al.*, 2010). Strata correspond to intersections of 13 diameters classes dc (10 to 130 cm at breast height) and 6 forest types ft, i.e. intersections of species compositions sp and forest structures st : broadleaf high forests, mixed high forests, coniferous high forests, broadleaf forests with intermediate structure, mixed forests with intermediate structure and broadleaf coppices. Forests are categorized as mixed when both coniferous and broadleaf species make up more than 15 % of forest cover and are otherwise categorized as either broadleaf or coniferous. Forests are categorized as intermediate structure when both coppice and higher strata make up more than 25 % of forest cover and are otherwise categorized as high forests or coppices.

The resource is described at two spatial levels: 12 regions i and more than 8500 8km-wide pixels px (Figure A.1.3). At the regional level, initial volumes i for each strata are determined from National National Forest Inventory data[48]. At the pixel level, initial areas for each forest type are determined from Corine Landcover data[49] ($area_{px,sp}$) and regional ratios ($area_{px,sp,st}$, [A1.19]). Regional timber volumes are then distributed across pixels proportionately to their area shares (Lobianco *et al.*, 2015, [A1.20]).

[A1.19] $$area_{px,sp,st} = area_{px,sp} \frac{V_{i,sp,st}}{\sum_{st} V_{i,sp,st}} + area_{px,sp=mixed} \frac{V_{i,sp,st}}{\sum_{st} V_{i,sp,st}}$$

[A1.20] $$V_{px,ft,dc} = V_{i,ft,dc} \frac{area_{px,sp}}{area_{i,ft}}$$



48 https://ign.fr/
49 https://land.copernicus.eu/pan-european/corine-land-cover

Figure A.1.3 – Regional and pixel-level scales in the FFSM

Products supply (and hence harvests) is determined at the regional level as a function of available timber inventories [A1.3]. These are computed as the sum of timber volumes in pixels within a region multiplied by binary coefficients $flag$ indicating which strata can be used to manufacture a given product, weighted by pixel-specific availability coefficients $avail$ (between 0 and 1) which depend on accessibility (mean elevation) and the presence of protected areas [A1.21]. Conversely, regional product supplies are translated back into pixel-level harvest volumes using the same distribution key [A1.22].

$$[A1.21] \quad F_{w,i,t} = \sum_{px,ft,dc} flag_{ft,dc,w} * avail_{px} * V_{px,ft,dc,t}$$

$$[A1.22] \quad hV_{px,ft,dc,t} = \left(\sum_{w} flag_{ft,dc,w} \frac{S_{wi,t}}{F_{wi,t}} \right) * avail_{px} * V_{px,ft,dc,t}$$

Volumes within a strata are updated through a yearly recursion [A1.23]. For a given strata, the change in volume takes into account harvested volumes hV and mortality rate m in that strata during the past year, as well as timber growth into and outside of the strata. The latter are represented with times of passage tp (i.e. the time needed to be promoted to the next diameter class) and shape parameters β when moving up a diameter class. In the end, volume updates are given as:

$$[A1.23] \quad V_{px,ft,dc,t} = V_{px,ft,dc,t-1} \left(1 - m_{pxft,dc,t} - \frac{1}{tp_{px,ft,dc,t}} \right) - hV_{px,ft,dc,t} + \frac{V_{px,ft,dc-1,t-1} * \beta_{i,ft,dc}}{tp_{px,ft,dc-1,t}}$$

Within a region, tree growth and mortality are modelled to be heterogeneous across pixels. Pixel-specific multipliers $mult$ are drawn from a normal distribution of average 1 and standard deviation equal to standard deviation in regional inventory data. Besides, the user also has the possibility to introduce exogenous multipliers $exoMult$ to define changes in growth conditions (example for times of passage in [A1.24]).

$$[A1.24] \quad tp_{px,ft,dc,t} = tp_{px,ft,dc,t=0} * mult_{px,ft,dc,t} * exoMult_{px,ft,dc,t}$$

A.3. FFSM Forest management ("Area Allocation") module

The FFSM assumes that density is constant within a given strata, and computes harvested areas $hArea$ from harvested volumes and timber densities vHa, themselves computed recursively by diameter class as a function of times of passage and mortality rates [A1.25-26].

$$[A1.25] \quad hArea_{px,ft,dc,t} = hV_{px,ft,dc,t} \; / \; vHa_{px,ft,dc,t}$$

$$[A1.26] \quad vHa_{px,ft,dc,t} = vHa_{px,ft,dc-1,t} * \beta_{i,ft,dc} * \left(1 - (1 - m_{pxft,dc,t})^{tp_{px,ft,dc,t}} \right)$$

Harvested areas within a pixel are then attributed to the forest type with highest expected returns[50] following the Land Expectation Value criterion (Faustmann, 1849), computed as an expected annual income $\overline{eai}$ with discount rate r [A1.27-28]. $\overline{eai}$ is calculated at the moment t when the decision is made but concerns a future time $t+T$ when the final harvest occurs. Hence, it is computed from expected products prices $\bar{P}$ and expected volumes per hectare $\overline{vHa}$. A binary variable $harvestFlag$ indicates whether the harvest is a final felling or not, and T is defined as the cumulative time of passage to reach a given diameter class.

$$[A1.27] \quad max_{ft}(\overline{eai}_{px,ft,t})$$

$$[A1.28] \quad \overline{eai}_{px,ft,t} = max_{dc,w}\left(\frac{\overline{P}_{i,w,t+T} * \overline{vHa}_{px,ft,dc,t+T} * flag_{ft,dc,w} * harvestFlag_{ft,dc,w} * r}{(1+r)^T - 1}\right)$$

For a given product, prices $\bar{P}_{r,w,t+T}$ expected at year t for year $t+T$ are computed as the mean between current prices in the region $P_{r,w,t}$ and expected prices in the region [A1.29]. The latter are themselves computed from current prices in the region, current international prices $P_{RoW,w,t}$ and expected international prices $\bar{P}_{RoW,w,t+T}$, which the user defines as an exogenous parameter. The mean is weighted with parameter k, which defines the owners' level of confidence in current prices versus expected prices.

$$[A1.29] \quad \overline{P}_{i,w,t+T} = (1-k_{px}) * P_{i,w,t} + k_{px} * P_{i,w,t} * \frac{\overline{P}_{RoW,w,t+T}}{P_{RoW,w,t}}$$

Similarly, expected densities $\overline{vHa}$ are computed given applying the approach from equation [A1.26], this time using a weighted average between current values for times of passage and mortality rates and expected values, i.e. values defined using exogenous multipliers in equation [A1.24].

A.4. Carbon storage in FFSM

A carbon accounting (CA) module was developed for the FFSM in Lobianco *et al.* (2016) and tracks carbon stocks and flows in forest biomass and harvested wood products, avoided emissions due to substitution effects and the forest sector's own emissions from transportation and transformation activities. This thesis only addresses carbon storage: we here give an overview of how the CA module represents it.

Carbon in forest biomass is tracked in 3 separate compartments: inventoried biomass (i.e. tree stems), non-inventoried biomass (i.e. branches, roots) and dead biomass. Carbon in inventoried biomass is determined by applying a carbon density coefficient to available timber inventories (in m^3) computed by the resource module. Carbon in non-inventoried biomass is determined by first using an expansion factor to obtain its value (in m^3) from inventoried biomass and then by applying a carbon density coefficient (Table A.1.1). Inventoried timber (and associated carbon) is removed from the compartment at the moment of the yearly recursion following two processes: harvests and mortality. Losses due to the latter are

[50] The user can also define a parameter between 0 and 1 indicating the share of harvested area concerned by the regeneration decision. The remaining area is attributed to the forest type present before harvest.

transferred to the dead biomass carbon pool, where it undergoes an exponential decay process of the form $C_t = C_{t=0} * e^{-kt}$ where k is a function of half-decay time.

Table A.1.1 - Value ranges for parameters in the carbon accounting module (Lobianco, Caurla, *et al.*, 2016).

Description	Values	Unit
Carbon density in inventoried biomass	833-981	kgCO2eq/m3
Carbon density in non-inventoried biomass	833-981	kgCO2eq/m3
Carbon density in products	833-981	kgCO2eq/m3
Ratio of inventoried to non-inventoried biomass	0,716-0,764	NA
Half-decay time for dead biomass from inventoried resources	26-43	years
Half-decay time for dead biomass from non-inventoried resources	10	years
Half-decay time for products	2-13	years

A similar approach is used for harvested wood products, which enter the products pool at the moment of harvest and also undergo an exponential decay process. Recycling of primary products is explicitly considered in coefficients used for input-output transformation processes, while end-of-life recycling for transformed products is implicitly considered by extending half-decay times for such products. The CA module follows a production approach and does not account for primary products sold abroad, nor for secondary products imported from abroad.

2. Appendix B – Supplementary material for chapter 2

B.1. Search query

(TITLE-ABS-KEY ((*"partial equilibrium"* OR *"spatial equilibrium"* OR *"price equilibrium"* OR *"spatial price equilibrium"* OR *"trade model*"* OR *"optimi?ation model*"* OR *"optimal control"* OR *"dynamic model"* OR *"economic model*"* OR *"intertemporal model*"* OR *"mathematical programming model*"* OR *"positive mathematical programming"* OR *"intertemporal optimi?ation"* OR *"dynamic optimi?ation"* OR *"global model*"* OR *"projection model*"* OR *"market model"*)
AND ((*forest* AND *sector*) OR ((*timber* OR *wood* OR *"wood product*"* OR *lumber* OR *roundwood* OR *softwood* OR *log?* OR (*biomass* W/3 (*forest* OR *woo d*))) W/5 (*market** OR *supply* OR *demand* OR *trade*))))
OR
(TITLE-ABS-KEY (*"forest and agriculture optimisation model"* OR *"FASOMGHG"* OR *"FASOM-GHG"* OR *"FASOM"* OR *"global forest products model"* OR *"french forest sector model"* OR *"timber supply model"* OR ((*"sub-regional timber supply"* OR *"subregional timber supply"*) AND *model*) OR (*"SF-GTM"* AND *forest* AND *finland*) OR (*"NTM"* AND *forest* AND *norway*) OR (*"NorFor"* AND *f orest* AND *norway*) OR *"EFI-GTM"* OR *"FOHOW"* OR (*"fiber allocation model"* AND *forest*) OR *"REPA-FTM"* OR *"timber projection model"* OR *"Global Timber Model"* OR *"Nordic Forest Sector Model"* OR (*"NFSM"* AND *forest* AND *sector*) OR *"Global Forest Trade Model"* OR *"forest sector model*"*)))
AND
(LIMIT-TO (DOCTYPE , *"ar "*) OR LIMIT-TO (DOCTYPE , *" cp "*) OR LIMIT-TO (DOCTYPE , *" re "*)) AND (LIMIT-TO (LANGUAGE , "English") OR LIMIT-TO (LANGUAGE , "French"))

B.2. List of articles

1. Abbott B., Stennes B., van kooten G.C., (2009). Mountain pine beetle, global markets, and the British Columbia forest economy. Canadian Journal of Forest Research.
2. Abdul-Rahim A.S., Mohd Shahwahid H.O., Mad-Nasir S., Awang-Noor A.G., (2012). Assessing the economic impact of sustainable forest management practices on the timber market in peninsular Malaysia. Malaysian Forester.
3. Abt R.C., Cubbage F.W., Abt K.L., (2009). Projecting southern timber supply for multiple products by subregion. Forest Products Journal.
4. Abt R.C., Cubbage F.W., Pacheco G., (2000). Southern forest resource assessment using the subregional timber supply (SRTS) model. Forest Products Journal.
5. Adams D.M., Alig R., Latta G., White E.M., (2011). Regional impacts of a program for private forest carbon offset sales. Journal of Forestry.
6. Adams D.M., Alig R.J., Callaway J.M., McCarl B.A., Winnett S.M., (1996). The forest and agricultural sector optimization model (FASOM): model structure and policy applications. Research Paper - US Department of Agriculture, Forest Service.
7. Adams D.M., Alig R.J., McCarl B.A., Callaway J.M., Winnett S.M., (1996). An analysis of the impacts of public timber harvest policies on private forest management in the United States. Forest Science.
8. Adams D.M., Alig R.J., McCarl B.A., Winnett S.M., Callaway J.M., (1998). The effects of factor supply assumptions on interemporal timber supply behavior: The cases of investable funds and land. Canadian Journal of Forest Research.
9. Adams D.M., Haynes R.W., (1996). The 1993 timber assessment market model: Structure, projections, and policy simulations. USDA Forest Service - General Technical Report PNW.
10. Adams D.M., Latta G.S., (2005). Costs and regional impacts of restoration thinning programs on the national forests in eastern Oregon. Canadian Journal of Forest Research.
11. Adams D.M., Latta G.S., (2007). Timber trends on private lands in western Oregon and Washington: A new look. Western Journal of Applied Forestry.

12. Adams D.M., Latta G.S., (2007). Future prospects for private timber harvest in eastern Oregon. Western Journal of Applied Forestry.
13. Alig R., Adams D., McCarl B., Callaway J.M., Winnett S., (1997). Assessing effects of mitigation strategies for global climate change with an intertemporal model of the U.S. forest and agriculture sectors. Environmental and Resource Economics.
14. Alig R., Adams D., Mills J., Haynes R., Ince P., Moulton R., (2001). Alternative projections of the impacts of private investment on southern forests: A comparison of two large-scale forest sector models of the United States. Silva Fennica.
15. Alig R., Latta G., Adams D., McCarl B., (2010). Mitigating greenhouse gases: The importance of land base interactions between forests, agriculture, and residential development in the face of changes in bioenergy and carbon prices. Forest Policy and Economics.
16. Alig R.J., (2005). Methods for projecting large-scale area changes for U.S. land uses and land covers: The past and the future. USDA Forest Service - General Technical Report PNW.
17. Alig R.J., Adams D.M., Chmelik J.T., Bettinger P., (1999). Private forest investment and long-run sustainable harvest volumes. New Forests.
18. Alig R.J., Adams D.M., McCarl B.A., (2002). Projecting impacts of global climate change on the US forest and agriculture sectors and carbon budgets. Forest Ecology and Management.
19. Alig R.J., Bair L.S., (2006). Forest environmental investments and implications for climate change mitigation. Journal of Environmental Quality.
20. Barbier E.B., (1999). The effects of the Uruguay Round tariff reductions on the forest product trade: A partial equilibrium analysis. World Economy.
21. Barbier E.B., Bockstael N., Burgess J.C., Strand I., (1995). The Linkages between the Timber Trade and Tropical Deforestation—Indonesia. World Economy.
22. Beach R.H., Cai Y., Thomson A., Zhang X., Jones R., McCarl B.A., Crimmins A., Martinich J., Cole J., Ohrel S., Deangelo B., McFarland J., Strzepek K., Boehlert B., (2015). Climate change impacts on US agriculture and forestry: Benefits of global climate stabilization. Environmental Research Letters.
23. Bernard J.-T., Bouthillier L., Catimel J., Gélinas N., (1997). An integrated model of Québec-Ontario-U.S. Northeast softwood lumber markets. American Journal of Agricultural Economics.
24. Binkley C.S., Cornelis Van Kooten G., (1994). Integrating climatic change and forests: Economic and ecologic assessments. Climatic Change.
25. Bolkesjø T.F., (2005). Projecting pulpwood prices under different assumptions on future capacities in the pulp and paper industry. Silva Fennica.
26. Bolkesjø T.F., Trømborg E., Solberg B., (2005). Increasing forest conservation in Norway: Consequences for timber and forest products markets. Environmental and Resource Economics.
27. Böttcher H., Frank S., Havlík P., Elbersen B., (2013). Future GHG emissions more efficiently controlled by land-use policies than by bioenergy sustainability criteria. Biofuels, Bioproducts and Biorefining.
28. Boyd R., Doroodian K., Abdul-Latif S., (1993). The Effects of Tariff Removals on the North American Lumber Trade. Canadian Journal of Agricultural Economics.
29. Brackley A.M., Haynes R.W., (2008). Timber products output and timber harvests in Alaska: An addendum. USDA Forest Service - Research Note PNW-RN.
30. Brackley A.M., Rojas T.D., Haynes R.W., (2006). Timber products output and timber harvests in Alaska: Projections for 2005-25. USDA Forest Service - General Technical Report PNW.
31. Brazee R., Mendelsohn R., (1990). A dynamic model of timber markets. Forest Science.
32. Brooks D.J., Ferrante J.A., Haverkamp J., Bowles I., Lange W., Darr D., (2001). Economic and environmental effects of accelerated tariff liberalization in the forest products sector. General Technical Reports of the US Department of Agriculture, Forest Service.
33. Brooks D.J., Haynes R.W., (1997). Timber products output and timber harvests in Alaska: Projections for 1997-2010. USDA Forest Service - General Technical Report PNW.
34. Buongiorno J., (2014). Global modelling to predict timber production and prices: The GFPM approach. Forestry.
35. Buongiorno J., (1996). Forest sector modeling: A synthesis of econometrics, mathematical programming, and system dynamics methods. International Journal of Forecasting.
36. Buongiorno J., Johnston C., Zhu S., (2017). An assessment of gains and losses from international trade in the forest sector. Forest Policy and Economics.
37. Buongiorno J., Raunikar R., Zhu S., (2011). Consequences of increasing bioenergy demand on wood and forests: An application of the Global Forest Products Model. Journal of Forest Economics.
38. Buongiorno J., Rougieux P., Barkaoui A., Zhu S., Harou P., (2014). Potential impact of a Transatlantic Trade and Investment Partnership on the global forest sector. Journal of Forest Economics.
39. Buongiorno J., Zhu S., (2017). Potential effects of a Trans-Pacific Partnership on forest industries. Forest Policy and Economics.

40. Buongiorno J., Zhu S., (2013). Consequences of carbon offset payments for the global forest sector. Journal of Forest Economics.
41. Buongiorno J., Zhu S., (2014). Assessing the impact of planted forests on the global forest economy. New Zealand Journal of Forestry Science.
42. Buongiorno J., Zhu S., (2015). Technical change in forest sector models: the global forest products model approach. Scandinavian Journal of Forest Research.
43. Buongiorno, J. (2018). Projected effects of us tariffs on canadian softwood lumber and newsprint imports: A cobweb model. Canadian Journal of Forest Research.
44. Buongiorno, J., Johnston, C. (2018). Effects of parameter and data uncertainty on long-term projections in a model of the global forest sector. Forest Policy and Economics.
45. Buongiorno, J., Johnston, C. (2018). Potential effects of US protectionism and trade wars on the global forest sector. Forest Science.
46. Busby G.M., Montgomery C.A., Latta G.S., (2007). The opportunity cost of forest certification on private land in western Oregon. Western Journal of Applied Forestry.
47. Cardellichio P.A., Adams D.M., (1990). An appraisal of the IIASA model of the global forest sector: advances, shortcomings, and implications for future research. Forest Science.
48. Caurla S., (2013). A typology and history of business models for the forestry sector [Une typologie et une histoire des modèles économiques de secteur forestier]. Revue Forestiere Francaise.
49. Caurla S., (2014). The FFSM 1.0 model - A research tool in economics used as a decision-making aid [Le modèle FFSM 1.0: De l'outil de recherche en économie à son utilisation pour l'aide à la décision]. Revue Forestiere Francaise.
50. Caurla S., Delacote P., Lecocq F., Barkaoui A., (2013). Stimulating fuelwood consumption through public policies: An assessment of economic and resource impacts based on the French Forest Sector Model. Energy Policy.
51. Caurla S., Delacote P., Lecocq F., Barthès J., Barkaoui A., (2013). Combining an inter-sectoral carbon tax with sectoral mitigation policies: Impacts on the French forest sector. Journal of Forest Economics.
52. Caurla S., Garcia S., Niedzwiedz A., (2015). Store or export? An economic evaluation of financial compensation to forest sector after windstorm. The case of Hurricane Klaus. Forest Policy and Economics.
53. Caurla, S., Bertrand, V., Delacote, P., Le Cadre, E. (2018). Heat or power: How to increase the use of energy wood at the lowest cost. Energy Economics.
54. Chang W.-Y., Gaston C., (2014). The competitiveness of Canadian softwood lumber: A disaggregated trade-flow analysis. Canadian Journal of Forest Research.
55. Chang W.-Y., Gaston C., (2016). A trade flow analysis of the global softwood log market: Implications of Russian log export tax reduction and New Zealand log production restriction. Forestry.
56. Cheng B.-D., Diao G., Wang Y.-B., (2014). Modeling China's forest resources and timber supply. International Conference on Management Science and Engineering - Annual Conference Proceedings.
57. Chudy R.P., Sjølie H.K., Solberg B., (2016). Incorporating risk in forest sector modeling – state of the art and promising paths for future research. Scandinavian Journal of Forest Research.
58. Chudy, R.P., Sjolie, H.K., Latta, G.S., Solberg, B. (2019). Effects on forest products markets of second-generation biofuel production based on biomass from boreal forests: a case study from Norway. Scandinavian Journal of Forest Research.
59. Costanza J.K., Abt R.C., McKerrow A.J., Collazo J.A., (2017). Bioenergy production and forest landscape change in the southeastern United States. GCB Bioenergy.
60. Cubbage F.W., Hogg D.W., Harris T.G., Alig R.J., (1990). Inventory projection with the Georgia Regional Timber Supply (GRITS) model. Southern Journal of Applied Forestry.
61. Daigneault A., Sohngen B., Sedjo R., (2012). Economic approach to assess the forest carbon implications of biomass energy. Environmental Science and Technology.
62. Daigneault A.J., Sohngen B., Sedjo R., (2008). Exchange rates and the competitiveness of the United States timber sector in a global economy. Forest Policy and Economics.
63. Devadoss S., Aguiar A.H., (2006). Effects of global trade liberalization on softwood lumber markets. Applied Economics.
64. Devadoss S., Aguiar A.H., Shook S.R., Araji J., (2005). A spatial equilibrium analysis of U.S.-Canadian disputes on the world softwood lumber market. Canadian Journal of Agricultural Economics.
65. Duden A.S., Verweij P.A., Junginger H.M., Abt R.C., Henderson J.D., Dale V.H., Kline K.L., Karssenberg D., Verstegen J.A., Faaij A.P.C., van der Hilst F., (2017). Modeling the impacts of wood pellet demand on forest dynamics in southeastern United States. Biofuels, Bioproducts and Biorefining.

66. Earles J.M., Halog A., Ince P., Skog K., (2013). Integrated Economic Equilibrium and Life Cycle Assessment Modeling for Policy-based Consequential LCA. Journal of Industrial Ecology.
67. Eriksson Lo & al (2012). Climate change mitigation through increased wood use in the European construction sector-towards an integrated modelling framework. European Journal of Forest Research.
68. Favero, A., Mendelsohn, R., Sohngen, B. (2018). Can the Global Forest Sector Survive 11 Â°c Warming?. Agricultural and Resource Economics Review.
69. Fernandez, M.A., Daigneault, A.J. (2018). Money does grow on trees: Impacts of the Paris agreement on the New Zealand economy. Climate Change Economics.
70. Flatberg, T., Norstebo, V.S., Bjorkelo, K., Astrup, R., Sovde, N.E. (2018). A mathematical model for infrastructure investments in the forest sector of coastal Norway. Forest Policy and Economics.
71. Folsland Bolkesjø T., Trømborg E., Solberg B., (2006). Bioenergy from the forest sector: Economic potential and interactions with timber and forest products markets in Norway. Scandinavian Journal of Forest Research.
72. Galik C.S., Abt R.C., (2016). Sustainability guidelines and forest market response: An assessment of European Union pellet demand in the southeastern United States. GCB Bioenergy.
73. Galik C.S., Abt R.C., Latta G., Méley A., Henderson J.D., (2016). Meeting renewable energy and land use objectives through public-private biomass supply partnerships. Applied Energy.
74. Galik C.S., Abt R.C., Latta G., Vegh T., (2015). The environmental and economic effects of regional bioenergy policy in the southeastern U.S. Energy Policy.
75. Gautier A., Lamond B.F., Paré D., Rouleau F., (2000). The Québec ministry of natural resources uses linear programming to understand the wood-fiber market. Interfaces.
76. Geijer E., Andersson J., Bostedt G., Brännlund R., Hjältén J., (2014). Safeguarding species richness vs. increasing the use of renewable energy-The effect of stump harvesting on two environmental goals. Journal of Forest Economics.
77. Geijer E., Bostedt G., Brännlund R., (2011). Damned if you do, damned if you do not-Reduced Climate Impact vs. Sustainable Forests in Sweden. Resource and Energy Economics.
78. Gong P., Löfgren K.-G., Rosvall O., (2013). Economic evaluation of biotechnological progress: The effect of changing management behavior. Natural Resource Modeling.
79. Guan, Z., Ip Ping Sheong, J.K.F. (2019). The Restricting Effects of Forest Certification on the International Trade of Wood Products. Journal of Sustainable Forestry.
80. Guo J., Gong P., (2017). The potential and cost of increasing forest carbon sequestration in Sweden. Journal of Forest Economics.
81. Guo Z., Hodges D.G., Abt R.C., (2011). Forest biomass supply for bioenergy production and its impacts on roundwood markets in tennessee. Southern Journal of Applied Forestry.
82. Haim D., White E.M., Alig R.J., (2015). Agriculture afforestation for carbon sequestration under carbon markets in the United States: Leakage behavior from regional allowance programs. Applied Economic Perspectives and Policy.
83. Haim D., White E.M., Alig R.J., (2014). Permanence of agricultural afforestation for carbon sequestration under stylized carbon markets in the U.S.. Forest Policy and Economics.
84. Hänninen R., Kallio A.M.I., (2007). Economic impacts on the forest sector of increasing forest biodiversity conservation in Finland. Silva Fennica.
85. Harkonen, S., Neumann, M., Mues, V., Berninger, F., Bronisz, K., Cardellini, G., Chirici, G., Hasenauer, H., Koehl, M., Lang, M., Merganicova, K., Mohren, F., Moiseyev, A., Moreno, A., Mura, M., Muys, B., Olschofsky, K., Del Perugia, B., Rorstad, P.K., Solberg, B., Thivolle-Cazat, A., Trotsiuk, V., Makela, A. (2019). A climate-sensitive forest model for assessing impacts of forest management in Europe. Environmental Modelling and Software.
86. Hauer G., Cumming S., Schmiegelow F., Adamowicz W., Weber M., Jagodzinski R., (2010). Tradeoffs between forestry resource and conservation values under alternate policy regimes: A spatial analysis of the western Canadian boreal plains. Ecological Modelling.
87. Havlík P., Schneider U.A., Schmid E., Böttcher H., Fritz S., Skalský R., Aoki K., Cara S.D., Kindermann G., Kraxner F., Leduc S., McCallum I., Mosnier A., Sauer T., Obersteiner M., (2011). Global land-use implications of first and second generation biofuel targets. Energy Policy.
88. Haynes R., (2003). Economic analysis in support of broad scale land management strategies. Forest Policy and Economics.
89. Hedenus F., Azar C., (2009). Bioenergy plantations or long-term carbon sinks? - A model based analysis. Biomass and Bioenergy.
90. Hieu P.S., Harrison S., (2011). A review of the formulation and application of the spatial equilibrium models to analyze policy. Journal of Forestry Research.

91. Hovi I.B., Madslien A., Sjølie H., Solberg B., Trømborg E., Veisten K., (2011). Impacts of combining partial and general equilibrium modelling in freight transport analyses - a forest sector case study from Norway. Transportation Planning and Technology.
92. Hu Y., Perez-Garcia J., Robbins A., Liu Y., Liu F., (2015). China's role in the global forest sector: how will the US recovery and a diminished Chinese demand influence global wood markets?. Scandinavian Journal of Forest Research.
93. Hultkrantz L., (1991). The cost of edible fish-Effects on the Swedish and finnish forest industries from the imposition of effluent charges on chlorine residuals in Sweden. Journal of Environmental Management.
94. Hurmekoski, E., Sjolie, H.K. (2018). Comparing forest sector modelling and qualitative foresight analysis: Cases on wood products industry. Journal of Forest Economics.
95. Kallio, A.M., Solberg, B. (2018). Leakage of forest harvest changes in a small open economy: case Norway. Scandinavian Journal of Forest Research.
96. Im E.H., Adams D.M., Latta G.S., (2010). The impacts of changes in federal timber harvest on forest carbon sequestration in western Oregon. Canadian Journal of Forest Research.
97. Ince P.J., Kramp A., Skog K.E., (2012). Evaluating Economic Impacts of Expanded Global Wood Energy Consumption with the USFPM/GFPM Model. Canadian Journal of Agricultural Economics.
98. Ince P.J., Kramp A.D., Skog K.E., Yoo D.-I., Sample V.A., (2011). Modeling future U.S. forest sector market and trade impacts of expansion in wood energy consumption. Journal of Forest Economics.
99. Ince P.J., Spelter H., Skog K.E., Kramp A., Dykstra D.P., (2008). Market impacts of hypothetical fuel treatment thinning programs on federal lands in the western United States. Forest Policy and Economics.
100. Jastad, E.O., Bolkesjo, T.F., Tromborg, E., Rorstad, P.K. (2019). Large-scale forest-based biofuel production in the Nordic forest sector: Effects on the economics of forestry and forest industries. Energy Conversion and Management.
101. Jastad, E.O., Mustapha, W.F., Bolkesjo¸, T.F., Tromborg, E., Solberg, B. (2018). Modelling of uncertainty in the economic development of the Norwegian forest sector. Journal of Forest Economics.
102. Jiang W., Searle S., Siddiqui S., (2017). Analysis of the global wood-chip trade's response to renewable energy policies using a spatial price equilibrium model. Biofuels, Bioproducts and Biorefining.
103. Jiang, W., Carter, D.R., Fu, H., Jacobson, M.G., Zipp, K.Y., Jin, J., Yang, L. (2019). The impact of the biomass crop assistance program on the united states forest products market: An application of the global forest products model. Forests.
104. Johnston C.M.T., (2016). Global paper market forecasts to 2030 under future internet demand scenarios. Journal of Forest Economics.
105. Johnston C.M.T., Buongiorno J., (2017). Impact of Brexit on the forest products industry of the United Kingdom and the rest of the world. Forestry.
106. Johnston C.M.T., Parajuli R., (2017). What's next in the U.S.-Canada softwood lumber dispute? An economic analysis of restrictive trade policy measures. Forest Policy and Economics.
107. Johnston C.M.T., van Kooten G.C., (2017). Impact of inefficient quota allocation under the Canada-U.S. softwood lumber dispute: A calibrated mixed complementarity approach. Forest Policy and Economics.
108. Johnston C.M.T., Van Kooten G.C., (2014). Economic consequences of increased bioenergy demand. Forestry Chronicle.
109. Johnston C.M.T., van Kooten G.C., (2016). Global trade impacts of increasing Europe's bioenergy demand. Journal of Forest Economics.
110. Jonsson R., Rinaldi F., (2017). The impact on global wood-product markets of increasing consumption of wood pellets within the European Union. Energy.
111. Jonsson R., Rinaldi F., Räty M., Sallnäs O., (2016). Integrating forest-based industry and forest resource modeling. IForest.
112. Jonsson, R., Blujdea, V.N.B., Fiorese, G., Pilli, R., Rinaldi, F., Baranzelli, C., Camia, A. (2018). Outlook of the European forest-based sector: Forest growth, harvest demand, wood-product markets, and forest carbon dynamics implications. Iforest.
113. Joyce L.A., Mills J.R., Heath L.S., McGuire A.D., Haynes R.W., Birdsey R.A., (1995). Forest sector impacts from changes in forest productivity under climate change. Journal of Biogeography.
114. Kallio A.M.I., (2001). Analysing the Finnish pulpwood market under alternative hypotheses of competition. Canadian Journal of Forest Research.
115. Kallio A.M.I., (2010). Accounting for uncertainty in a forest sector model using Monte Carlo simulation. Forest Policy and Economics.

116. Kallio A.M.I., Chudy R., Solberg B., (2018). Prospects for producing liquid wood-based biofuels and impacts in the wood using sectors in Europe. Biomass and Bioenergy.
117. Kallio A.M.I., Hänninen R., Vainikainen N., Luque S., (2008). Biodiversity value and the optimal location of forest conservation sites in Southern Finland. Ecological Economics.
118. Kallio A.M.I., Moiseyev A., Solberg B., (2006). Economic impacts of increased forest conservation in Europe: a forest sector model analysis. Environmental Science and Policy.
119. Kallio, A.M.I., Solberg, B. (2018). On the reliability of international forest sector statistics: Problems and needs for improvements. Forests.
120. Kallio, A.M.I., Solberg, B., Kaar, L., Paivinen, R. (2018). Economic impacts of setting reference levels for the forest carbon sinks in the EU on the European forest sector. Forest Policy and Economics.
121. Kangas H.-L., Lintunen J., Pohjola J., Hetemäki L., Uusivuori J., (2011). Investments into forest biorefineries under different price and policy structures. Energy Economics.
122. Kim, S.J., Baker, J.S., Sohngen, B.L., Shell, M. (2018). Cumulative global forest carbon implications of regional bioenergy expansion policies. Resource and Energy Economics.
123. Kinnucan H.W., Zhang D., (2004). Incidence of the 1996 Canada-U.S. softwood lumber agreement and the optimal export tax. Canadian Journal of Agricultural Economics.
124. Krutilla K., (1991). Transportation specification in forest trade models. Forest Science.
125. Latta G., Adams D.M., Alig R.J., White E., (2011). Simulated effects of mandatory versus voluntary participation in private forest carbon offset markets in the United States. Journal of Forest Economics.
126. Latta G.S., Adams D.M., Bell K.P., Kline J.D., (2016). Evaluating land-use and private forest management responses to a potential forest carbon offset sales program in western Oregon (USA). Forest Policy and Economics.
127. Latta G.S., Baker J.S., Beach R.H., Rose S.K., McCarl B.A., (2013). A multi-sector intertemporal optimization approach to assess the GHG implications of U.S. forest and agricultural biomass electricity expansion. Journal of Forest Economics.
128. Latta G.S., Baker J.S., Ohrel S., (2018). A Land Use and Resource Allocation (LURA) modeling system for projecting localized forest CO2 effects of alternative macroeconomic futures. Forest Policy and Economics.
129. Latta G.S., Sjølie H.K., Solberg B., (2013). A review of recent developments and applications of partial equilibrium models of the forest sector. Journal of Forest Economics.
130. Lauri P., Havlík P., Kindermann G., Forsell N., Böttcher H., Obersteiner M., (2014). Woody biomass energy potential in 2050. Energy Policy.
131. Lauri P., Kallio A.M.I., Schneider U.A., (2012). Price of CO 2 emissions and use of wood in Europe. Forest Policy and Economics.
132. Lauri P., Kallio M., Schneider U.A., (2013). The future development of the use of wood in Russia and its potential impacts on the EU forest sector. Scandinavian Journal of Forest Research.
133. Lecocq F., Caurla S., Delacote P., Barkaoui A., Sauquet A., (2011). Paying for forest carbon or stimulating fuelwood demand? Insights from the French Forest Sector Model. Journal of Forest Economics.
134. Lee D.M., Lyon K.S., (2004). A Dynamic Analysis of the Global Timber Market under Global Warming: An Integrated Modeling Approach. Southern Economic Journal.
135. Lee H.-C., McCarl B.A., Gillig D., (2005). The dynamic competitiveness of U.S. agricultural and forest carbon sequestration. Canadian Journal of Agricultural Economics.
136. Lenglet J., Courtonne J.-Y., Caurla S., (2017). Material flow analysis of the forest-wood supply chain: A consequential approach for log export policies in France. Journal of Cleaner Production.
137. Lobianco A., Caurla S., Delacote P., Barkaoui A., (2016). Carbon mitigation potential of the French forest sector under threat of combined physical and market impacts due to climate change. Journal of Forest Economics.
138. Lobianco A., Delacote P., Caurla S., Barkaoui A., (2015). The importance of introducing spatial heterogeneity in bio-economic forest models: Insights gleaned from FFSM++. Ecological Modelling.
139. Lobianco A., Delacote P., Caurla S., Barkaoui A., (2016). Accounting for Active Management and Risk Attitude in Forest Sector Models: An Impact Study on French Forests. Environmental Modeling and Assessment.
140. Lundmark R., (2007). Dependencies between forest products sectors: A partial equilibrium analysis. Forest Products Journal.
141. Martinkus N., Latta G., Morgan T., Wolcott M., (2017). A comparison of methodologies for estimating delivered forest residue volume and cost to a wood-based biorefinery. Biomass and Bioenergy.

142. McCarl B.A., Adams D.M., Alig R.J., Burton D., Chen C.-C., (2000). Effects of global climate change on the US forest sector: Response functions derived from a dynamic resource and market simulator. Climate Research.
143. Merry F., Soares-Filho B., Nepstad D., Amacher G., Rodrigues H., (2009). Balancing conservation and economic sustainability: The future of the amazon timber industry. Environmental Management.
144. Mogus A., Stennes B., Van Kooten G.C., (2006). Canada-U.S. softwood lumber trade revisited: Substitution bias in the context of a spatial price equilibrium framework. Forest Science.
145. Moiseyev A., Solberg B., Kallio A.M.I., (2014). The impact of subsidies and carbon pricing on the wood biomass use for energy in the EU. Energy.
146. Moiseyev A., Solberg B., Kallio A.M.I., (2013). Wood biomass use for energy in Europe under different assumptions of coal, gas and CO2 emission prices and market conditions. Journal of Forest Economics.
147. Moiseyev A., Solberg B., Kallio A.M.I., Lindner M., (2011). An economic analysis of the potential contribution of forest biomass to the EU RES target and its implications for the EU forest industries. Journal of Forest Economics.
148. Moiseyev A., Solberg B., Michie B., Kallio A.M.I., (2010). Modeling the impacts of policy measures to prevent import of illegal wood and wood products. Forest Policy and Economics.
149. Monge, J.J., Wakelin, S.J. (2019). Geographically-explicit, dynamic partial equilibrium model of regional primary value chains â€“ Mathematical formulation and application to forestry in the Northland region of New Zealand. Computers and Electronics in Agriculture.
150. Morland, C., Schier, F., Janzen, N., Weimar, H. (2018). Supply and demand functions for global wood markets: Specification and plausibility testing of econometric models within the global forest sector. Forest Policy and Economics.
151. Mosnier A., Havlík P., Obersteiner M., Aoki K., Schmid E., Fritz S., McCallum I., Leduc S., (2014). Modeling Impact of Development Trajectories and a Global Agreement on Reducing Emissions from Deforestation on Congo Basin Forests by 2030. Environmental and Resource Economics.
152. Murray B.C., McCarl B.A., Lee H.-C., (2004). Estimating leakage from forest carbon sequestration programs. Land Economics.
153. Mustapha W.F., Bolkesjø T.F., Martinsen T., Trømborg E., (2017). Techno-economic comparison of promising biofuel conversion pathways in a Nordic context – Effects of feedstock costs and technology learning. Energy Conversion and Management.
154. Mustapha, W.F., Kirkerud, J.G., Bolkesjo, T.F., Tromborg, E. (2019). Large-scale forest-based biofuels production: Impacts on the Nordic energy sector. Energy Conversion and Management.
155. Mustapha, W.F., Tromborg, E., Bolkesjo, T.F. (2019). Forest-based biofuel production in the Nordic countries: Modelling of optimal allocation. Forest Policy and Economics.
156. Nanang D.M., Hauer G.K., (2006). Estimating the costs of overlapping tenure constraints: a case study in Northern Alberta, Canada. Forest Policy and Economics.
157. Nepal P., Skog K.E., McKeever D.B., Bergman R.D., Abt K.L., Abt R.C., (2016). Carbon mitigation impacts of increased softwood lumber and structural panel use for nonresidential construction in the United States. Forest Products Journal.
158. Nepal, P., Korhonen, J., Prestemon, J.P., Cubbage, F.W. (2019). Projecting global planted forest area developments and the associated impacts on global forest product markets. Journal of Environmental Management.
159. Niquidet K., Friesen D., (2014). Bioenergy potential from wood residuals in Alberta: A positive mathematical programming approach. Canadian Journal of Forest Research.
160. Niquidet K., Stennes B., van Kooten G.C., (2012). Bioenergy from Mountain Pine Beetle Timber and Forest Residuals: A Cost Analysis. Canadian Journal of Agricultural Economics.
161. Northway S., Bull G.Q., Nelson J.D., (2013). Forest sector partial equilibrium models: Processing components. Forest Science.
162. Okoro, S.U., Schickhoff, U., Schneider, U.A. (2018). Impacts of bioenergy policies on land-use change in Nigeria. Energies.
163. Olofsson, E. (2019). Regional effects of a green steel industryâ€“fuel substitution and feedstock competition. Scandinavian Journal of Forest Research.
164. Paradis G., Bouchard M., LeBel L., D'Amours S., (2018). A bi-level model formulation for the distributed wood supply planning problem. Canadian Journal of Forest Research.
165. Pattanayak S.K., Abt R.C., Sommer A.J., Cubbage F., Murray B.C., Yang J.-C., Wear D., Ahn S., (2004). Forest forecasts: Does individual heterogeneity matter for market and landscape outcomes?. Forest Policy and Economics.
166. Pearson T.R.H., Brown S., Sohngen B., Henman J., Ohrel S., (2014). Transaction costs for carbon sequestration projects in the tropical forest sector. Mitigation and Adaptation Strategies for Global Change.

167. Perez-Garcia J., Joyce L.A., Binkley C.S., McGuire A.D., (2009). Economic impacts of climatic change on the global forest sector: An integrated ecological/economic assessment. Critical Reviews in Environmental Science and Technology.
168. Perez-Garcia J., Joyce L.A., McGuire A.D., (2002). Temporal uncertainties of integrated ecological/economic assessments at the global and regional scales. Forest Ecology and Management.
169. Perez-Garcia J., Joyce L.A., Mcguire A.D., Xiao X., (2002). Impacts of climate change on the global forest sector. Climatic Change.
170. Perez-Garcia J., Lippke B., Baker J., (1997). Trade barriers in the Pacific forest sector: Who wins and who loses. Contemporary Economic Policy.
171. Perez-Garcia J.M., (1995). Global economic and land use consequences of North American timberland withdrawals. Journal of Forestry.
172. Peter B., Niquidet K., (2016). Estimates of residual fibre supply and the impacts of new bioenergy capacity from a forest sector transportation model of the Canadian Prairie Provinces. Forest Policy and Economics.
173. Petucco, C., Lobianco, A., Caurla, S. (2019). Economic Evaluation of an Invasive Forest Pathogen at a Large Scale: The Case of Ash Dieback in France. Environmental Modeling and Assessment.
174. Polyakov M., Teeter L., (2007). Modeling pulpwood trade within the United States South. Forest Science.
175. Polyakov M., Wear D.N., Huggett R.N., (2010). Harvest choice and timber supply models for forest forecasting. Forest Science.
176. Prestemon J.P., Abt K.L., Huggett Jr. R.J., (2008). Market impacts of a multiyear mechanical fuel treatment program in the U.S.. Forest Policy and Economics.
177. Prestemon J.P., Abt K.L., Koch F.H., Potter K.M., (2013). An economic assessment of mountain pine beetle timber. salvage in the west. Western Journal of Applied Forestry.
178. Prestemon J.P., Abt R.C., (2002). The southern timber market to 2040. Journal of Forestry.
179. Prestemon J.P., Turner J.A., Buongiorno J., Zhu S., Li R., (2008). Some timber product market and trade implications of an invasive defoliator: The case of Asian Lymantria in the United States. Journal of Forestry.
180. Prestemon J.P., Zhu S., Turner J.A., Buongiorno J., Li R., (2006). Forest product trade impacts of an invasive species: Modeling structure and intervention trade-offs. Agricultural and Resource Economics Review.
181. Raunikar R., Buongiorno J., Turner J.A., Zhu S., (2010). Global outlook for wood and forests with the bioenergy demand implied by scenarios of the Intergovernmental Panel on Climate Change. Forest Policy and Economics.
182. Rougieux, P., Damette, O. (2018). Reassessing forest products demand functions in Europe using a panel cointegration approach. Applied Economics.
183. Sacchelli S., Bernetti I., De Meo I., Fiori L., Paletto A., Zambelli P., Ciolli M., (2014). Matching socio-economic and environmental efficiency of wood-residues energy chain: A partial equilibrium model for a case study in Alpine area. Journal of Cleaner Production.
184. Sathaye J., Makundi W., Dale L., Chan P., Andrasko K., (2006). GHG mitigation potential, costs and benefits in global forests: A dynamic partial equilibrium approach. Energy Journal.
185. Schier, F., Morland, C., Janzen, N., Weimar, H. (2018). Impacts of changing coniferous and non-coniferous wood supply on forest product markets: a German scenario case study. European Journal of Forest Research.
186. Schleupner C., Schneider U.A., (2010). Effects of bioenergy policies and targets on European wetland restoration options. Environmental Science and Policy.
187. Schleupner C., Schneider U.A., (2013). Allocation of European wetland restoration options for systematic conservation planning. Land Use Policy.
188. Schwab O., Maness T., Bull G., Roberts D., (2009). Modeling the effect of changing market conditions on mountain pine beetle salvage harvesting and structural changes in the British Columbia forest products industry. Canadian Journal of Forest Research.
189. Schwarzbauer P., Stern T., (2010). Energy vs. material: Economic impacts of a "wood-for-energy scenario" on the forest-based sector in Austria - A simulation approach. Forest Policy and Economics.
190. Schwarzbauer P., Weinfurter S., Stern T., Koch S., (2015). Simulating possible impacts of roundwood procurement problems in Austria on wood-based energy production and forest-based industries. Biomass and Bioenergy.
191. Schwarzbauer P., Weinfurter S., Stern T., Koch S., (2013). Economic crises: Impacts on the forest-based sector and wood-based energy use in Austria. Forest Policy and Economics.
192. Sedjo R., Tian X., (2012). Does wood bioenergy increase carbon stocks in forests?. Journal of Forestry.

193. Sedjo R.A., Sohngen B., (2013). Wood as a Major Feedstock for Biofuel Production in the United States: Impacts on Forests and International Trade. Journal of Sustainable Forestry.
194. Self N.M., Turner J.A., (2009). Market access for New Zealand forest products: An economic and environmental case for development of alternative phytosanitary treatments. New Zealand Journal of Forestry Science.
195. Sendak P.E., Abt R.C., Turner R.J., (2003). Timber supply projections for Northern New England and New York: Integrating a market perspective. Northern Journal of Applied Forestry.
196. Siry J.P., Cubbage F.W., Malmquist A.J., (2001). Potential impacts of increased management intensities on planted pine growth and yield and timber supply modeling in the south. Forest Products Journal.
197. Sjølie H.K., Latta G.S., Adams D.M., Solberg B., (2011). Impacts of agent information assumptions in forest sector modeling. Journal of Forest Economics.
198. Sjølie H.K., Latta G.S., Solberg B., (2014). Impacts of the Kyoto Protocol on boreal forest climate change mitigation. Annals of Forest Science.
199. Sjølie H.K., Latta G.S., Solberg B., (2013). Potential impact of albedo incorporation in boreal forest sector climate change policy effectiveness. Climate Policy.
200. Sjølie H.K., Latta G.S., Solberg B., (2013). Dual discounting in climate change mitigation in the forest sector. Journal of Forest Economics.
201. Sjølie H.K., Latta G.S., Solberg B., (2016). Combining backcasting with forest sector projection models to provide paths into the future bio-economy. Scandinavian Journal of Forest Research.
202. Sjølie H.K., Latta G.S., Trømborg E., Bolkesjø T.F., Solberg B., (2015). An assessment of forest sector modeling approaches: conceptual differences and quantitative comparison. Scandinavian Journal of Forest Research.
203. Sjølie H.K., Trømborg E., Solberg B., Bolkesjø T.F., (2010). Effects and costs of policies to increase bioenergy use and reduce GHG emissions from heating in Norway. Forest Policy and Economics.
204. Sohngen B., Mendelsohn R., (1998). Valuing the Impact of Large-Scale Ecological Change in a Market: The Effect of Climate Change on U.S. Timber. American Economic Review.
205. Sohngen B., Mendelsohn R., (1997). A dynamic model of forest carbon storage in the United States during climatic change. Critical Reviews in Environmental Science and Technology.
206. Sohngen B., Mendelsohn R., Sedjo R., (1999). Forest management, conservation, and global timber markets. American Journal of Agricultural Economics.
207. Sohngen B., Mendelsohn R., Sedjo R., (2001). A Global Model of Climate Change Impacts on Timber Markets. Journal of Agricultural and Resource Economics.
208. Sohngen B., Sedjo R., (1998). A comparison of timber market models: Static simulation and optimal control approaches. Forest Science.
209. Sohngen B.L., Haynes R.W., (1997). The potential for increasing carbon storage in United States unreserved timberlands by reducing forest fire frequency: An economic and ecological analysis. Climatic Change.
210. Solberg B., Moiseyev A., Kallio A.M.I., (2003). Economic impacts of accelerating forest growth in Europe. Forest Policy and Economics.
211. Solberg B., Moiseyev A., Kallio A.M.I., Toppinen A., (2010). Forest sector market impacts of changed roundwood export tariffs and investment climate in Russia. Forest Policy and Economics.
212. Soliman T., Mourits M.C.M., van der Werf W., Hengeveld G.M., Robinet C., Lansink A.G.J.M.O., (2012). Framework for Modelling Economic Impacts of Invasive Species, Applied to Pine Wood Nematode in Europe. PLoS ONE.
213. Stennes B., Wilson B., (2005). An analysis of lumber trade restrictions in North America: Application of a spatial equilibrium model. Forest Policy and Economics.
214. Stennes B.K., Niquidet K., Cornelis van Kooten G., (2010). Implications of expanding bioenergy production from wood in British Columbia: An application of a regional wood fiber allocation model. Forest Science.
215. Stern T., Ledl C., Braun M., Hesser F., Schwarzbauer P., (2015). Biorefineries' impacts on the Austrian forest sector: A system dynamics approach. Technological Forecasting and Social Change.
216. Sun C., (2016). Timber market recovery after a hurricane. Forest Science.
217. Sun L., Bogdanski B.E.C., (2017). Trade incentives for importers to adopt policies to address illegally logged timber: The case of non-tropical hardwood plywood. Journal of Forest Economics.
218. Sun L., Bogdanski B.E.C., Stennes B., Kooten G.C.V., (2010). Impacts of tariff and non-tariff trade barriers on the global forest products trade: An application of the global forest product model. International Forestry Review.
219. Szabó L., Soria A., Forsström J., Keränen J.T., Hytönen E., (2009). A world model of the pulp and paper industry: Demand, emission scenarios to 2030. Environmental Science and Policy.

220. Szarka, N., Wolfbauer, J., Bezama, A. (2018). A systems dynamics approach for supporting regional decisions on the energetic use of regional biomass residues. Waste Management and Research.
221. Tavoni M., Sohngen B., Bosetti V., (2007). Forestry and the carbon market response to stabilize climate. Energy Policy.
222. Toppinen A., Kuuluvainen J., (2010). Forest sector modelling in Europe-the state of the art and future research directions. Forest Policy and Economics.
223. Trømborg E., Bolkesjø T.F., Solberg B., (2008). Biomass market and trade in Norway: Status and future prospects. Biomass and Bioenergy.
224. Trømborg E., Bolkesjø T.F., Solberg B., (2007). Impacts of policy means for increased use of forest-based bioenergy in Norway-A spatial partial equilibrium analysis. Energy Policy.
225. Trømborg E., Bolkesjø T.F., Solberg B., (2013). Second-generation biofuels: Impacts on bioheat production and forest products markets. International Journal of Energy Sector Management.
226. Trømborg E., Buongiorno J., Solberg B., (2000). The global timber market: Implications of changes in economic growth, timber supply, and technological trends. Forest Policy and Economics.
227. Trømborg E., Sjølie H., Solberg B., Hovi I.B., Madslien A., Veisten K., (2009). Economic and environmental impacts of transport cost changes on timber and forest product markets in Norway. Scandinavian Journal of Forest Research.
228. Trømborg E., Solberg B., (2010). Forest sector impacts of the increased use of wood in energy production in Norway. Forest Policy and Economics.
229. Turner J.A., Buongiorno J., Horgan G.P., Maplesden F.M., (2001). Liberalisation of forest product trade and the New Zealand forest sector, 2000-2015: A global modelling approach. New Zealand Journal of Forestry Science.
230. Turner J.A., Buongiorno J., Katz A., Zhu S., (2008). Implications of the Russian roundwood export tax for the Russian and global wood products sectors. Scandinavian Journal of Forest Research.
231. Turner J.A., Buongiorno J., Zhu S., (2005). Effects of the Free Trade Area of the Americas on forest resources. Agricultural and Resource Economics Review.
232. Turner J.A., Buongiorno J., Zhu S., (2006). An economic model of international wood supply, forest stock and forest area change. Scandinavian Journal of Forest Research.
233. Turner J.A., Buongiorno J., Zhu S., Maplesden F., (2008). Effect of non-tariff barriers on secondary processed wood product trade: New Zealand exports to the United States, China and Japan. New Zealand Journal of Forestry Science.
234. Turner J.A., Buongiorno J., Zhu S., Prestemon J.P., (2005). The U.S. forest sector in 2030: Markets and competitors. Forest Products Journal.
235. Turner J.A., Buongiorno J., Zhu S., Prestemon J.P., Li R., Bulman L.S., (2007). Modelling the impact of the exotic forest pest Nectria on the New Zealand forest sector and its major trading partners. New Zealand Journal of Forestry Science.
236. van Kooten G.C., Johnston C., (2014). Global impacts of Russian log export restrictions and the Canada-U.S. lumber dispute: Modeling trade in logs and lumber. Forest Policy and Economics.
237. Wang W., Dwivedi P., Abt R., Khanna M., (2015). Carbon savings with transatlantic trade in pellets: Accounting for market-driven effects. Environmental Research Letters.
238. White E.M., Latta G., Alig R.J., Skog K.E., Adams D.M., (2013). Biomass production from the U.S. forest and agriculture sectors in support of a renewable electricity standard. Energy Policy.
239. Whiteman Adrian, Brown Christopher, (2000). Modelling global forest products supply and demand: Recent results from FAO and their potential implications for New Zealand. New Zealand Journal of Forestry.
240. Wibe S., (2005). A simple simulation model for the forest sector. Journal of Forest Economics.
241. Yoshimoto A., Yukutake K., (2002). Japanese forest sector modeling through a partial equilibrium market model. Journal of Forest Research.
242. Yu, C.-H., McCarl, B.A. (2018). The water implications of greenhouse gas mitigation: Effects on land use, land use change, and forestry. Sustainability Switzerland.
243. Zhang H., Buongiorno J., Zhu S., (2012). Domestic and foreign consequences of China's land tenure reform on collective forests. International Forestry Review.
244. Zhang S., Gilless J.K., Stewart W., (2014). Modeling price-driven interactions between wood bioenergy and global wood product markets. Biomass and Bioenergy.
245. Zhang X., Xu B., Wang L., Yang A., Yang H., (2016). Eliminating illegal timber consumption or production: Which is the more economical means to reduce illegal logging?. Forests.
246. Zhu S., Buongiorno J., (2002). International impact of national environmental policies: The case of paper recycling in the United States. International Forestry Review.
247. Zhu S., Buongiorno J., Brooks D.J., (2001). Effects of accelerated tariff liberalization on the forest products sector: A global modeling approach. Forest Policy and Economics.

248. Zhu S., Turner J.A., Buongiorno J., (2008). Long-term economic impact of countervailing duties on coated free sheet paper imported by the United States from China, the Republic of Korea, and Indonesia. Forest Products Journal.

3. Appendix C – Supplementary material for chapter 3[51]

C.1. Distribution of growth multipliers

Figure C1.1. shows the distribution of growth multipliers for land allocated to each forest type, in BAU (no carbon pricing), compared to MAIN (with carbon prices). Growth multipliers come modify growth dynamics in each pixel, based on known regional distributions of times of passage between diameter classes. Mean growth multipliers are equal to 1 for all forest types. A growth multiplier under 1 means a growth faster than average (e.g. a multiplier of 0.5 means that times of passage to each diameter class are divided by 2). Distributions are skewed to the left, showing that forest types are most of the time chosen in locations where their growth is faster than average. In MAIN, forest types are less often chosen in locations where their growth multiplier is high. Data taken into account correspond to all choices throughout the simulation.

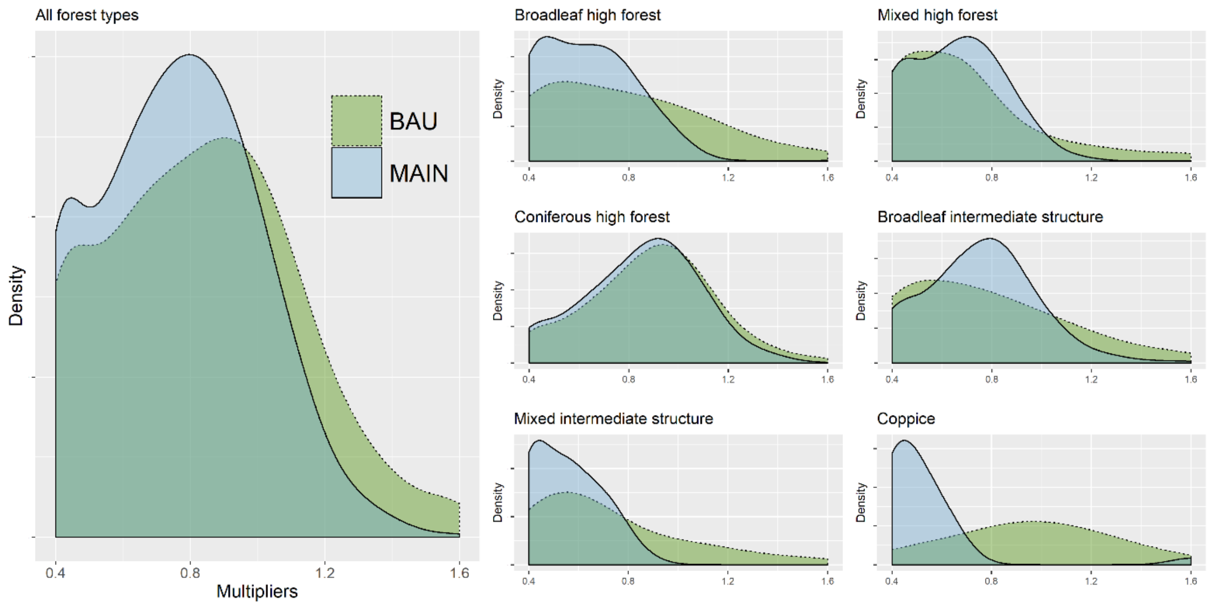


Figure C.1.1 – Distribution of growth multipliers for land allocated to each forest type in scenarios BAU and MAIN.

C.2. Additionality of carbon sequestration in relation to harvests, growth dynamics and forest cover.

Figure C.1.2. shows additional sequestration, calculated as the share of sequestration in MAIN in excess of that in BAU, for carbon sequestered from 2020 to 2100. Cumulative time of passage to the diameter class 60cm (the median diameter class in the model) is used as an indicator for growth speed in each region, averaged over all forest types. Average harvest changes are calculated over the whole simulation. The figure illustrates how additional carbon sequestration is primarily located in regions characterised by both (1) decreases in harvests and (2) fast growth dynamics, even when forest cover is low or moderate.

[51] Additional supplementary materials are available at Forestry online as an electronic file. These include results table disaggregated by 10-year periods.

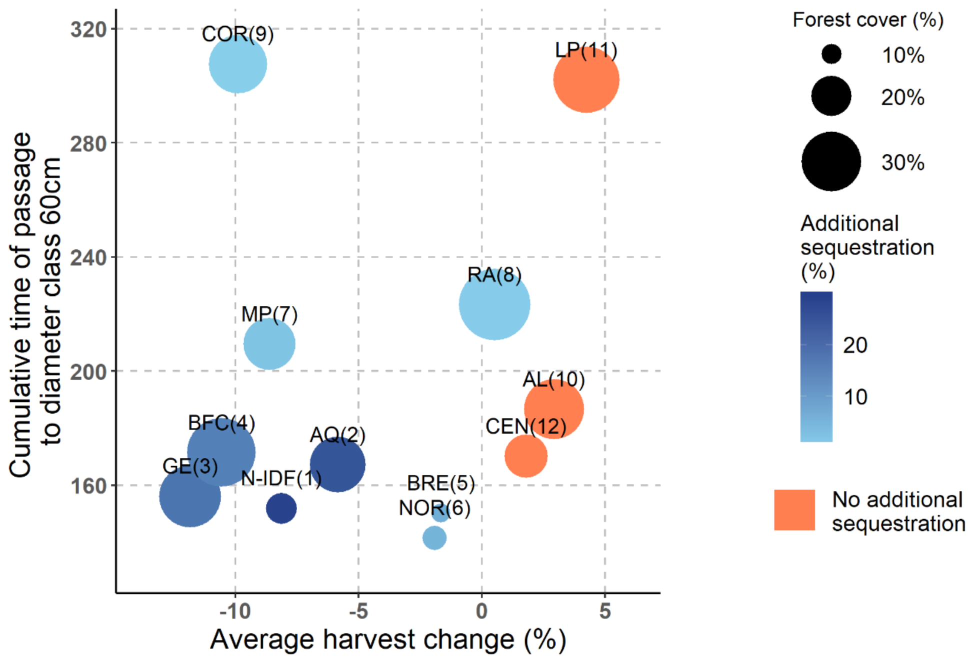


Figure C.2.1 – Regional additional carbon sequestration in relation with harvest change and growth dynamics.

C.3. Overview of regional investment decisions following harvests.

Tables C.3.1. and C.3.2. show changes in expected rotation lengths, cover change and investments after harvests at the regional level. Values correspond to scenario MAIN, are averaged over the whole simulation, and changes are given compared to BAU. These changes, over time, yield the landscape changes presented in the main text.

Table C.3.1 – Rotation lengths and cover changes after harvest

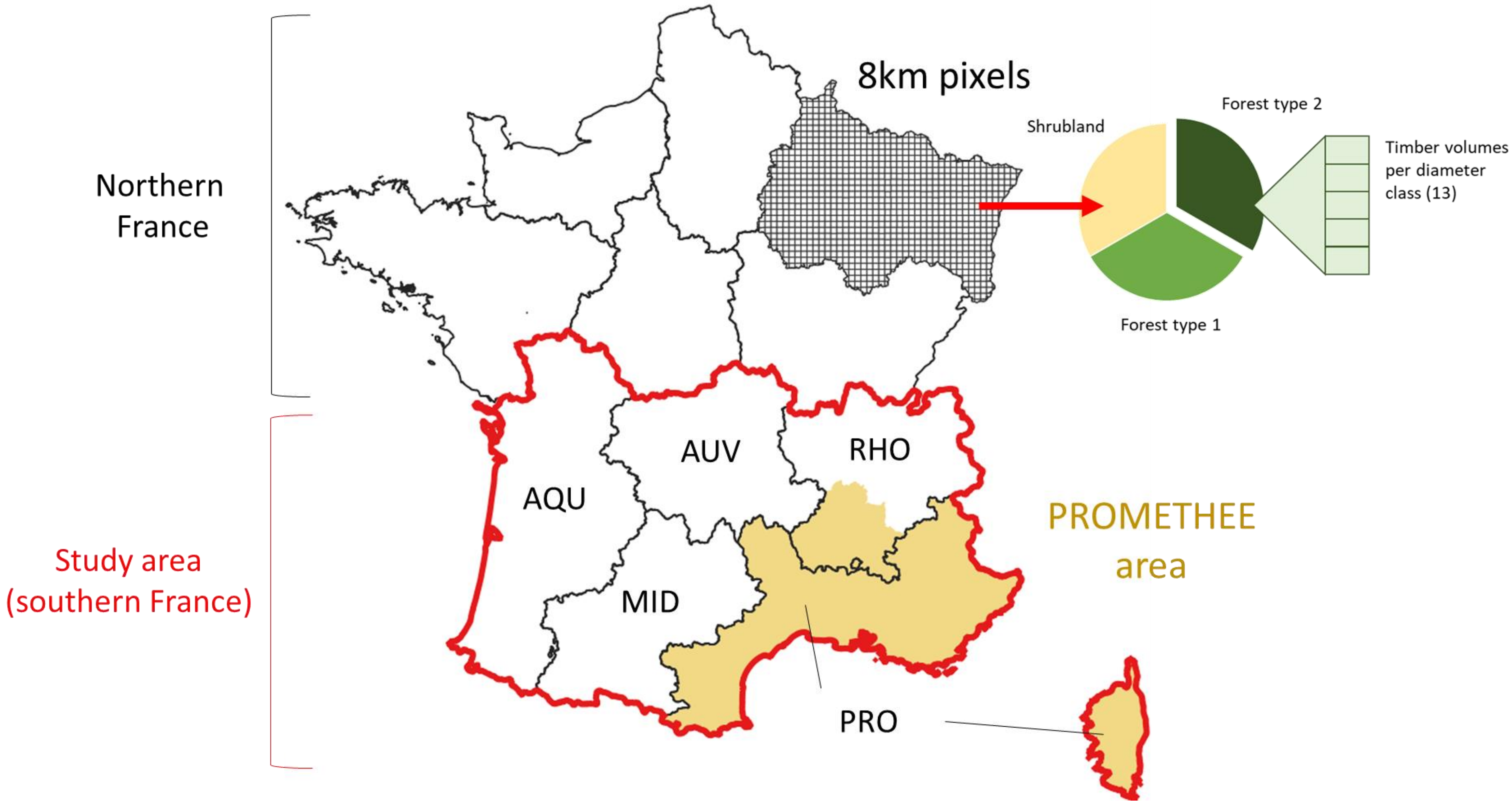
Region	Rotation length		Cover change	
GE	216,09	*(+127%)*	65.1%	*(+16.35)*
AQ	262,12	*(+215.2%)*	37.49%	*(+4.55)*
AL	218,07	*(+92.97%)*	63.42%	*(+32.38)*
NOR	172,88	*(+127.48%)*	69.25%	*(+4.08)*
BFC	209,97	*(+113.54%)*	60.95%	*(+15.49)*
BRE	217,19	*(+151.02%)*	56.02%	*(+8.49)*
CEN	283,52	*(+152.83%)*	74.95%	*(+8.34)*
COR	285,45	*(+113.22%)*	79.24%	*(+26.02)*
N-IDF	201,36	*(+123.49%)*	62.98%	*(+12.48)*
LP	250,02	*(+28.57%)*	71.48%	*(+49.42)*
MP	218,87	*(+84.62%)*	72.82%	*(+33.41)*
RA	224,21	*(+53.49%)*	60.35%	*(+42.84)*

Table C.3.2 – Investments following harvests (% ha)

Region	Share of investments (% of replanted areas)											
	Broadl. High forest		Mixed high forest		Conif. High forest		Broadl. interm. Str.		Mixed interm. Str.		Coppice	
GE	18.04%	*(-0.39)*	14.06%	*(+1.72)*	34.59%	*(-11.39)*	25.53%	*(+10.2)*	6.64%	*(-0.61)*	1.13%	*(+0.48)*
AQ	0.86%	*(+0.14)*	4.78%	*(+2.7)*	88.29%	*(-6.45)*	4.73%	*(+3.6)*	1.32%	*(+0.05)*	0.02%	*(-0.03)*
AL	3.36%	*(-3.4)*	26.12%	*(+11.44)*	44.24%	*(-19.14)*	12.89%	*(+8.07)*	13.39%	*(+3.41)*	0%	*(-0.38)*
NOR	5.85%	*(+0.27)*	7.23%	*(-1.92)*	74.98%	*(-3)*	9.79%	*(+4.05)*	2.14%	*(+0.65)*	0%	*0*
BFC	13.86%	*(+0.13)*	10.11%	*(+3.33)*	45.29%	*(-17.38)*	20.38%	*(+12.19)*	8.6%	*(+0.11)*	1.76%	*(+1.63)*
BRE	4.39%	*(+1.94)*	5.73%	*(-0.01)*	78.25%	*(-10.62)*	11.09%	*(+9.12)*	0.55%	*(-0.15)*	0%	*0*
CEN	0.59%	*(-4.26)*	0.07%	*(-1.6)*	91.6%	*(+5.09)*	7.74%	*(+1.42)*	0%	*(-0.41)*	0%	*0*
COR	21.36%	*(+11.63)*	13.02%	*(-2.22)*	28.13%	*(-6.8)*	25.47%	*(+2.23)*	10.06%	*(-4.31)*	1.96%	*(-0.53)*
N-IDF	31.82%	*(-1.95)*	10.89%	*(-0.99)*	21.39%	*(-3.76)*	29.6%	*(+8.81)*	4.15%	*(-2.62)*	2.16%	*(+0.51)*
LP	13.82%	*(+3.05)*	17.43%	*(+1.64)*	24.23%	*(-16.42)*	37.31%	*(+17.05)*	6.83%	*(-0.83)*	0.39%	*(-4.49)*
MP	6.16%	*(-6.97)*	31.24%	*(+16.62)*	35.27%	*(-16.5)*	17.24%	*(+7.76)*	10.1%	*(+0.57)*	0%	*(-1.48)*
RA	10.75%	*(+5.82)*	18.45%	*(+8.91)*	42.13%	*(-34.09)*	21.57%	*(+17.21)*	6.21%	*(+1.48)*	0.89%	*(+0.66)*

4. Appendix D – Supplementary material for chapter 4

D.1. Regions in the study area



D.2. Elements of evaluation for the fire activity model

The fire activity model was evaluated in the PROMETHEE region in Pimont et al. (in print) and shown to accurately reproduce observed fire activity patterns, with a slightly decreased performance for fires smaller than 50ha. Temporal trends (Figure D.2.1, left-hand side) are also correctly reproduced, except for fire occurrence for years 2004-2007 (slight consistent overestimation), which may be due to evolutions in fire suppression techniques and fire monitoring following the extreme 2003 fire season.

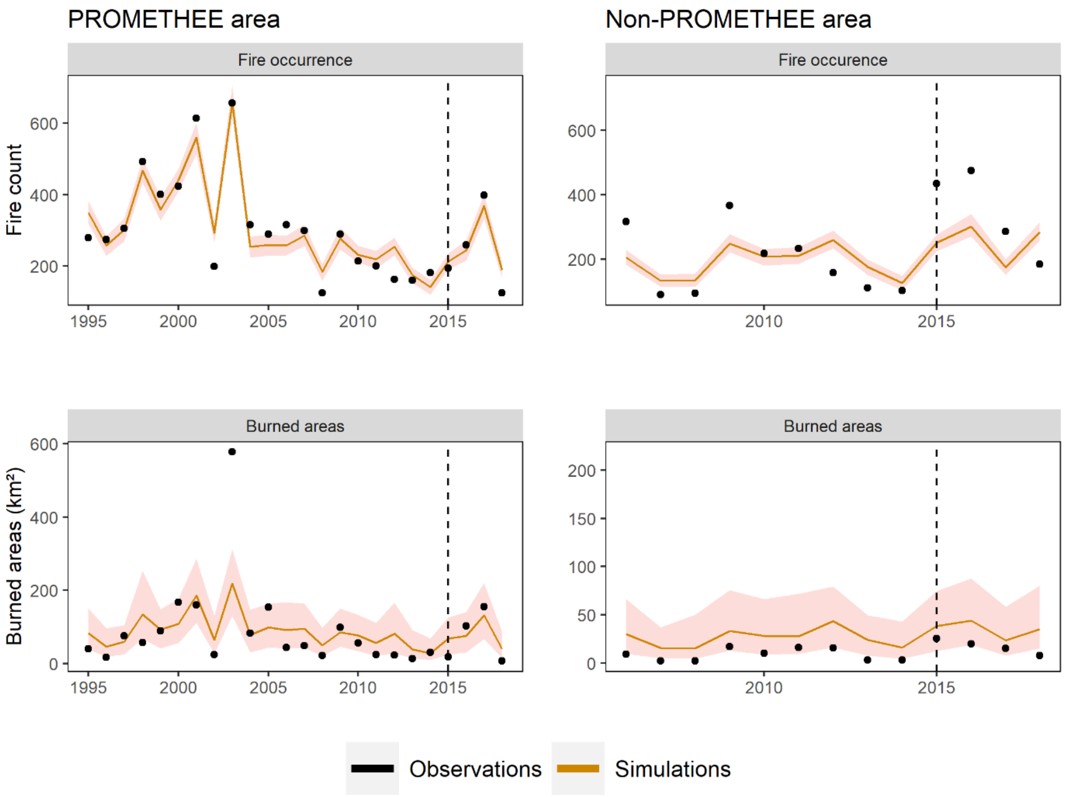


Figure D.2.1 - Simulated and observed fire activity in the study area. Data for observations in the PROMETHEE region (left, where the model is calibrated) are taken from the PROMETHEE database. Data for observations in the rest of Southern France (right) are taken from the BDIFF database and cover only 2006-2018. Observations after 2015 were only used for model validation (cf. Pimont et al., in print). Shaded areas represent 95% confidence intervals over 100 replications.

For the rest of the study area, simulations can only be compared to the BDIFF database for years after 2006. Results show temporal patterns to be quite accurately reproduced (Figure D.2.1, right-hand side). Values for burned areas most often fall within the confidence interval but are consistently over-estimated. This overestimation is in particular due to the model's lower accuracy in reproducing fire activity in the northernmost AUV and RHO regions, while accuracy is better in southern PRO, AQU and MID regions (Figure D.2.2., left-hand side). At the département level, bias in burned area simulations falls most often within ranges observed for the PROMETHEE area, and the most negative bias values are encountered in départements at the northern edge of the region and in some mountainous areas (Figure D.2.2, right-hand side). However, the many limitations of the BDIFF database hinder performing a more precise evaluation of the model. These limitations include the availability of only 12 years of data, inconsistent observation input across time and across départements, discrepancies in labelling fire types, and inconsistencies with the PROMETHEE database. These same reasons impede estimating a fire activity model outside the PROMETHEE area. The BDIFF database however offers good quality data on the territory of the GIP Agteri project, where bias values are similar to those in the PROMETHEE area. This suggests, as proposed by Fargeon (2019) in her evaluation of an earlier form of the model for the whole of France, that the fire activity model may be suitable outside the PROMETHEE area for a majority of Southern départements.

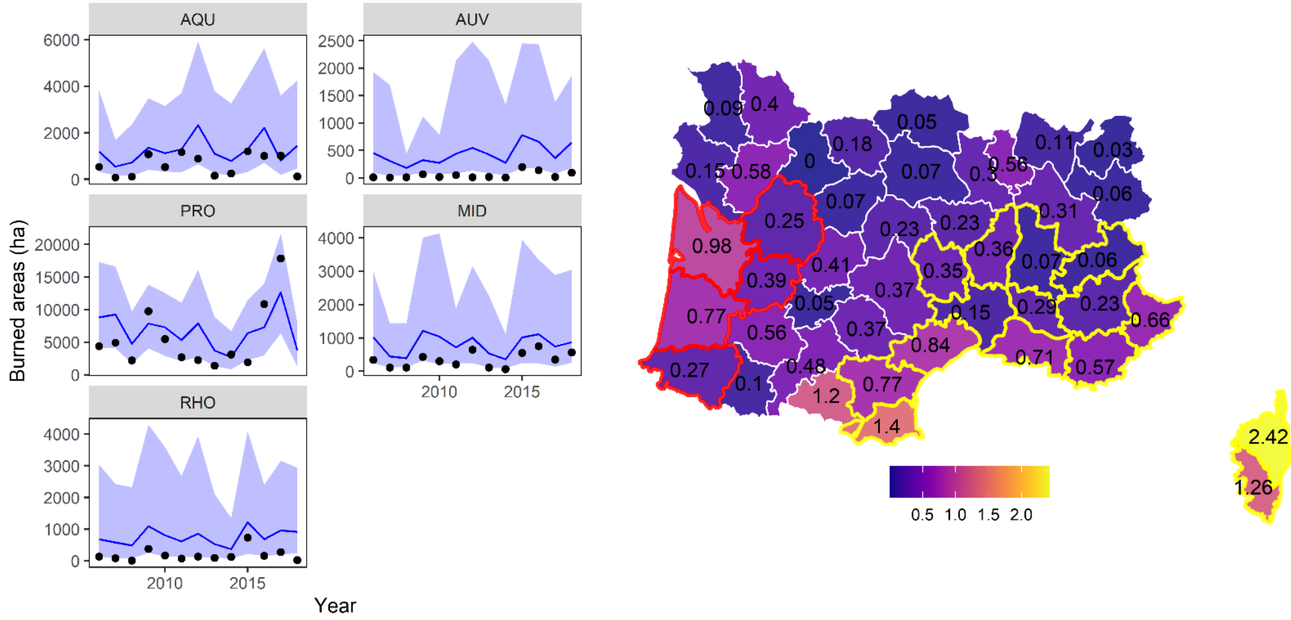


Figure D.2.2 – Simulated and observed burned areas in each of the FFSM model's region (left, annual values) and French administrative départements (right, cumulated values). Observations are retrieved from the BDIFF database for years 2006-2018. On the map, biases are computed as the ratio between cumulated observed burned areas and cumulated simulated burned areas. The PROMETHEE area is shown with yellow borders, the GIP Atgeri area with red borders.

D.3. Species composition in the study area

Charts in Figure D.3.1. show the distribution of regional timber volumes across the 17 main species identified in the study area. The 17 species all represent at least 5% of timber volumes in at least one region of the study area. Values are computed from resources inventoried in National Forest Inventory data (www.inventaire-forestier.ign.fr). Species are only shown when they represent at least 5% of regional timber volumes.

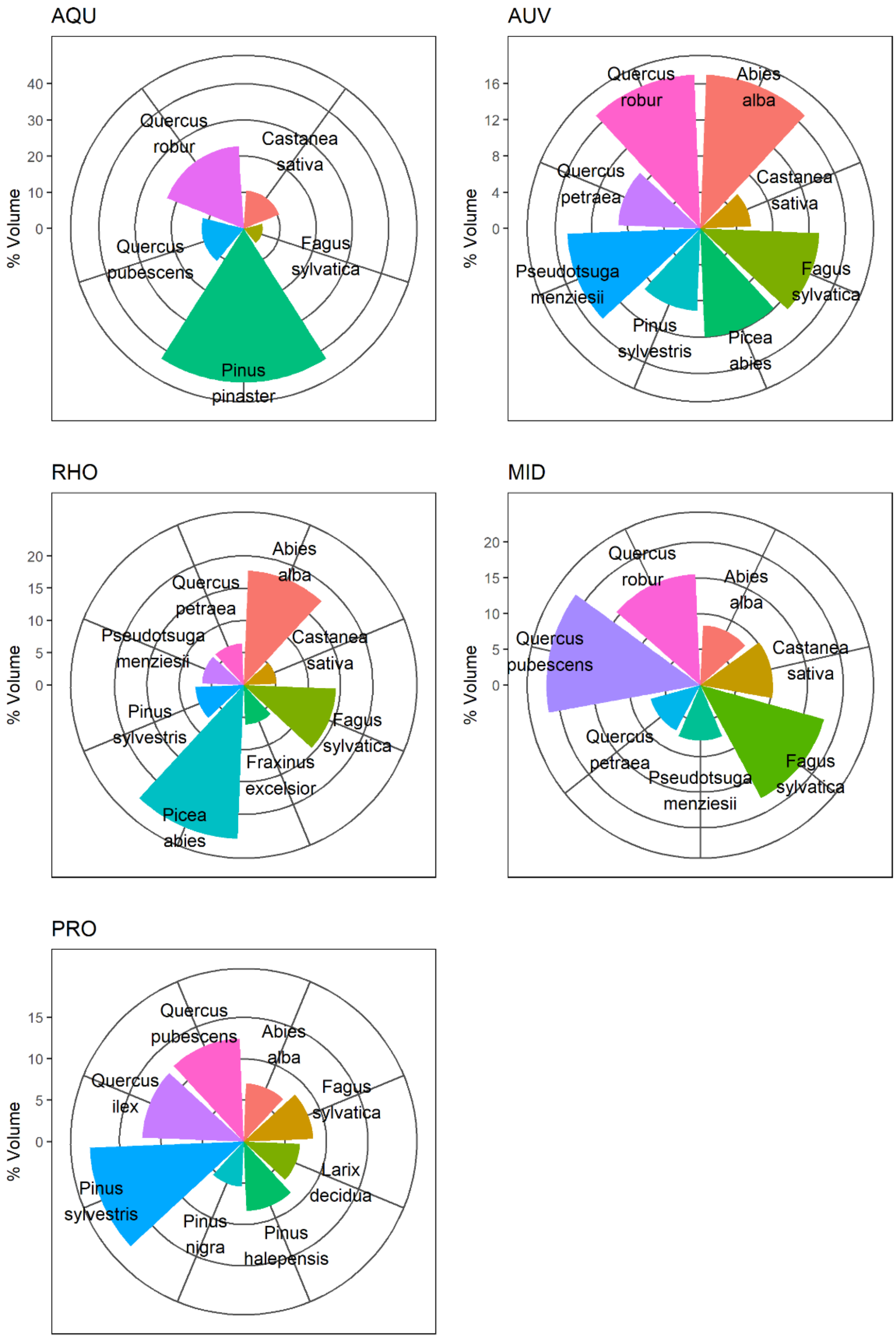


Figure D.3.1 – Distribution of forest volumes among 17 tree species in the regions of the study area.

D.4. Definition of species-specific mortality coefficients

Mortality coefficients used in fire-enabled DGVMs following the intermediate-complexity specification range from 0.72 to 0.93 for coniferous temperate PFTs and from 0.5 to 0.91 for broadleaf temperate PFTs (Thonicke *et al.*, 2001; Kloster *et al.*, 2010; Li, Zeng and Levis, 2012; Venevsky *et al.*, 2019). While they give guidance, these coefficients do not take into account aspects such as tree size and tree species, nor are they specific to Mediterranean Europe

Generic Ryan & Amman model

A generic model of post-fire tree mortality was developed by Ryan and Amman (1994) and expresses the probability of tree mortality (P_m, equation A4.1, Figure D.4.1.) as a function of bark thickness (BT, equation A4.2) and crown damage (crown volume scorched, CSV, equation A4.3). The approach has since been applied to new species and is often used in fire effects simulators (Hood *et al.*, 2007, 2018; Woolley *et al.*, 2012). For 60-70% crown volume scorched, i.e. a relatively high amount of damage typical of summer fires[52], thin-barked individuals (i.e. smaller trees) have mortality rates in the 80-100% range, while thick-barked individuals (i.e. larger trees) have mortality rates of 30% and below. When bark thickness takes intermediate values, there is a wider range of mortality rates. From these orders of magnitude, we define baseline mortality coefficient ranges for the three diameter class categories: over 80% (22.5cm and below), 40 to 60% (22.5 to 47.5cm) and less than 30% (over 47.5cm).

$$[A4.1] \quad P_m = \frac{1}{1 + e^{-1.941 + barkfactor + crownfactor}}$$

$$[A4.2] \quad barkfactor = 6.316 * \left(1 - e^{-0.3937 * BT}\right)$$

$$[A4.3] \quad crownfactor = -0.000535 * CVS^2$$

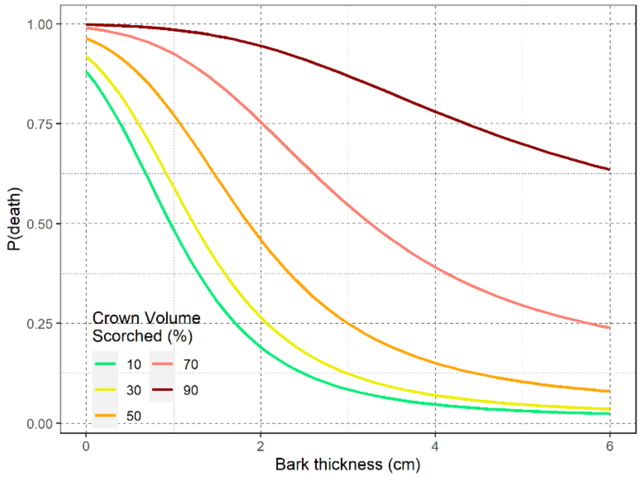


Figure D.4.1 – Post-fire probability of tree death as a function of bark thickness at breast height (cm) and crown volume scorched (% of crown volume) (Ryan and Amman, 1994).

52 For example, Rigolot (2004) report average values of 70-75% for fires in South Eastern France (pine species), and Catry (2010, 2013) values in the 60-100% range for most species in Portugal (broadleaves and pine species), both in the case of summer fires.

Pine species

For pine species, many empirical models of post-fire mortality have been developed in Portugal, France and Spain (Fernandes and Rigolot, 2007; Fernandes *et al.*, 2008a; Catry *et al.*, 2010, 2013; Garcia-Gonzalo *et al.*, 2011; Pimont, Prodon and Rigolot, 2011; Pimont *et al.*, 2014). Models have been developed for different species and calibrated from different datasets in different areas: there is not a single model, and models are hard to compare. As a result, we adapt baseline coefficients using general conclusions from the empirical literature, especially when species are compared (Fernandes *et al.*, 2008b; Pimont, Prodon and Rigolot, 2011; Keeley, 2012) and expert knowledge, but we avoid directly taking model results. Pine species have relatively thick bark, hence death usually comes from crown injury and observed average mortality rates range from 30-80%. Most species are well-adapted to resist low to moderate intensity fires, especially when diameter reaches 20-30cm, but trees remain vulnerable to high intensity fires. While most pines are to some degree “fire resistant” (e.g. Pinus nigra, Pinus pinaster), other are “fire tolerant” (e.g. Pinus pinea) and display lower average mortality rates, while others are “fire avoiders” and display high mortality rates (e.g. Pinus halepensis, Pinus nigra laricio), reflecting different strategies and plant traits (Fernandes *et al.*, 2008a; Keeley, 2012).

Mediterranean broadleaves

The empirical literature on other European species is scarcer (e.g. Dupire et al. 2019; Catry et al. 2013). Mediterranean broadleaf species have comparatively thinner bark than pines (e.g. Quercus ilex, Quercus pubescens) but can resprout from dormant buds and lethal damage usually comes from cambial damage. For example, in Portugal, Catry et al. (2010, 2013), report low average mortality rates (6.9%) for an ensemble of such species against 75% for pine trees, but 60% stem mortality in surviving broadleaf trees[53]. Exceptions include Quercus suber (very low mortality) and Castanea sativa (very high). We base our baseline coefficients for Mediterranean broadleaf species on the model developed for resprouting species top-kill probability ($P_{topkill}$, equation A4.4, Figure D.4.2.) by (Catry *et al.*, 2013)[54] as a function of Bole Char Height (BCH) and Diameter at Breast Height (DBH) and attribute higher/lower values to Castanea sativa and other species highlighted across the literature.

$$[A4.4] \quad P_{topkill} = \frac{1}{1 + e^{-0.076+0.05 * BCH - 0.121 * DBH}}$$

[53]The FFSM only models timber volumes in tree stems (marketable timber), hence top-kill is the metric we are interested in.

[54] We use 70% bole char height, indicated by authors to be typical of relatively intense summer fires. We increase values slightly to take into account that some trees will die directly during the fire.

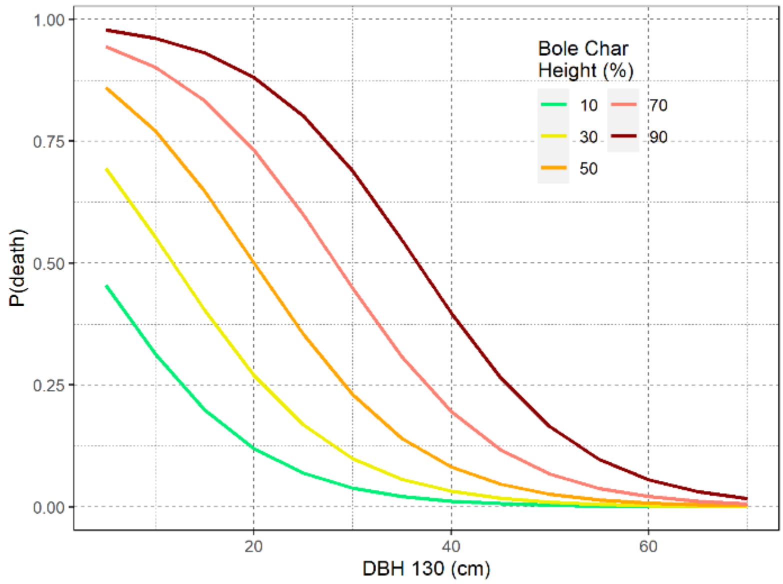


Figure D.4.2 – Probability of top-kill for surviving broadleaf species during summer fires in Portugal as a function of Bole Char Height (% tree height) and diameter at breast height (DBH) (Catry et al. 2013) .

Other species (temperate and subalpine)

Empirical models for other species in the study area are rare, but several recent studies have garnered knowledge on relationships between fire regimes, tree traits and mortality for the Alps (Conedera *et al.*, 2010; Maringer *et al.*, 2016; Fréjaville *et al.*, 2018; Fréjaville, Curt and Carcaillet, 2018; Dupire *et al.*, 2019). Results point to differences in species strategies regarding fire, with fire resistant species (thick bark, self-pruning) in lowland areas and fire avoiding species (thin bark, resources allocated to height growth) in elevated areas. The former are well adapted to low intensity surface fires, will sustain damage from higher intensity fires and show high mortality rates for small to medium diameter classes. They include Quercus robur and petraea, but also Larix decidua which, owing to its thicker bark, is more resistant, especially for medium to large diameters. Fire avoiding species will sustain damage more easily, even during less intense fire events. "Fire intolerant" species include Abies alba and Picea abies, which will sustain damage in low to medium diameter classes, while "fire sensitive species" include Fagus sylvatica with its very thin bark, as well as Castanea sativa. Both species are expected to sustain significant damage for most diameter classes, the former resprouting from the stool. Potential fire intensity is expected to increase at the dry margin of species distribution areas: sub-mediterranean and sub-alpine species may hence experience higher mortality rates in the decades to come. We defined coefficients consistent with such information and with those of other species, considering high intensity fires (summer weather).

Table D.4.1 – List of mortality coefficients used

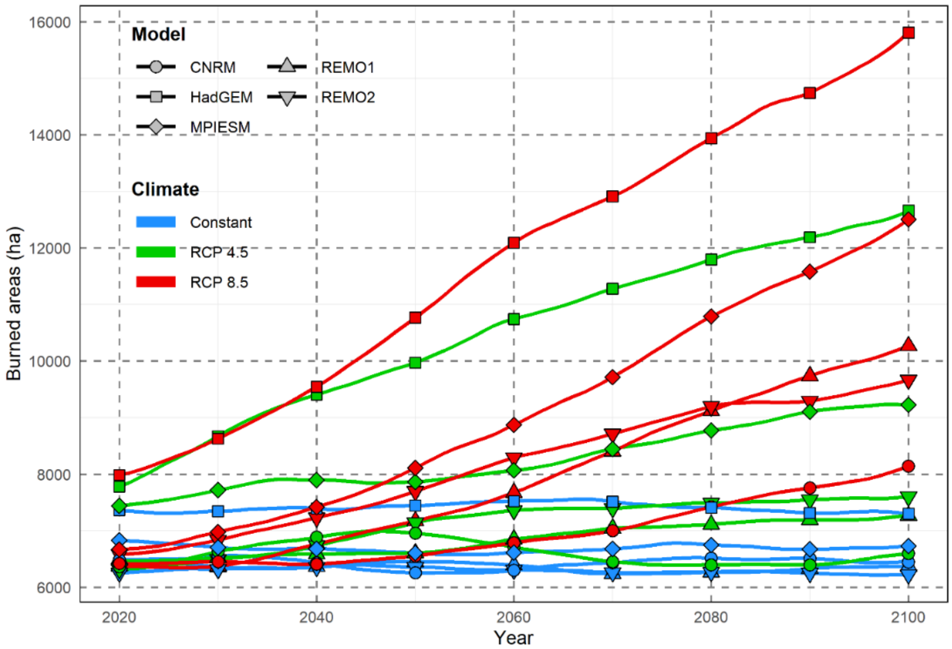
Species	Coefficient		
	<22,5cm	22,5-47,5cm	>47,5cm
Baseline	>0,8	0,4 to 0,6	<0,3
Pine species			
Pinus sylvestris	0,85	0,55	0,25
Pinus pinaster	0,8	0,5	0,2
Pinus nigra	0,8	0,5	0,2
Pinus halepensis	0,9	0,6	0,3
Pinus nigra laricio	0,85	0,55	0,25
Mediterranean broadleaves			
Quercus ilex	0,9	0,45	0,1
Quercus pubescens	0,9	0,45	0,1
Arbutus unedo	0,9	0,45	0,1
Sub-mediterranean & sub-alpine			
Fagus sylvatica	0,95	0,65	0,5
Castanea sativa	0,95	0,65	0,5
Picea abies	0,9	0,55	0,3
Abies alba	0,9	0,55	0,3
Quercus robur	0,85	0,5	0,25
Larix decidua	0,85	0,4	0,2
Quercus petraea	0,85	0,5	0,25
Fraxinus excelsior	0,85	0,55	0,3
Other species			
Pseudotsuga menziesii	0,85	0,5	0,2
Other coniferous	0,85	0,5	0,2
Other broadleaf	0,85	0,5	0,2

D.5. Evolution of simulated burned areas for different climate models

The GCM-RCM couples used in our study were selected by Fargeon et al. (2020) based on their suitability for Europe, the availability of daily simulation data over France and for several forcing levels, as well as to illustrate contrasting climate conditions in the future. In order for our analysis of uncertainties in forest sector dynamics to be consistent with that of Fargeon et al. for fire danger over the same area, we use the same couples and simulated weather data.

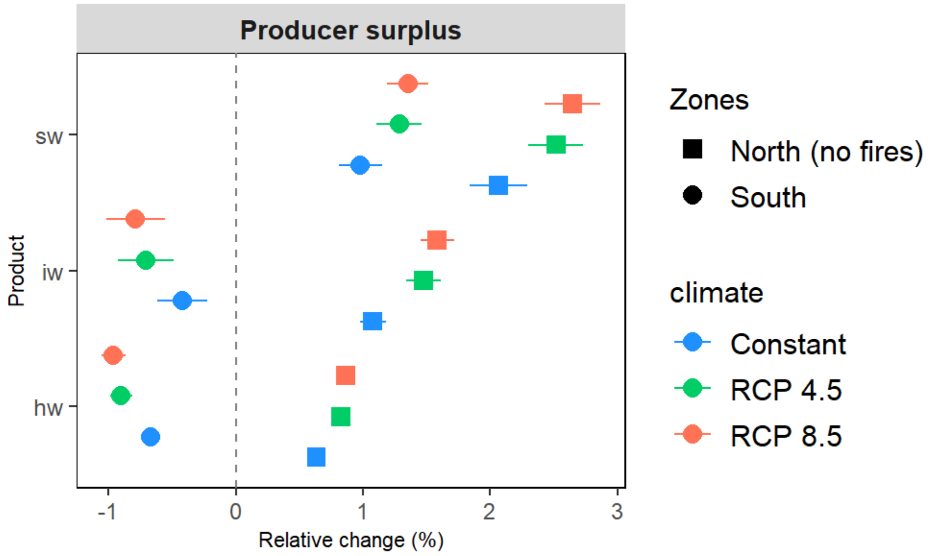
GCMs used are CNRM-CERFACS-CNRM-CM5, MOHC-HadGEM2-ES and MPI-M-MPI-ESM-LR. RCM RCA4 is used with all three GCMs, and two runs of RCM REMO2009 (run 1 and run 2) were used with GCM MPI-ESM. This yields 5 GCM-RCM couples, which we respectively name CNRM, HadGEM, MPI-ESM, REMO1 and REMO2.

Figure D.5.1 – Evolution of trends in burned areas for each GCM-RCM couple and each climate scenario. Values correspond to (smoothed) multi-replication trends.



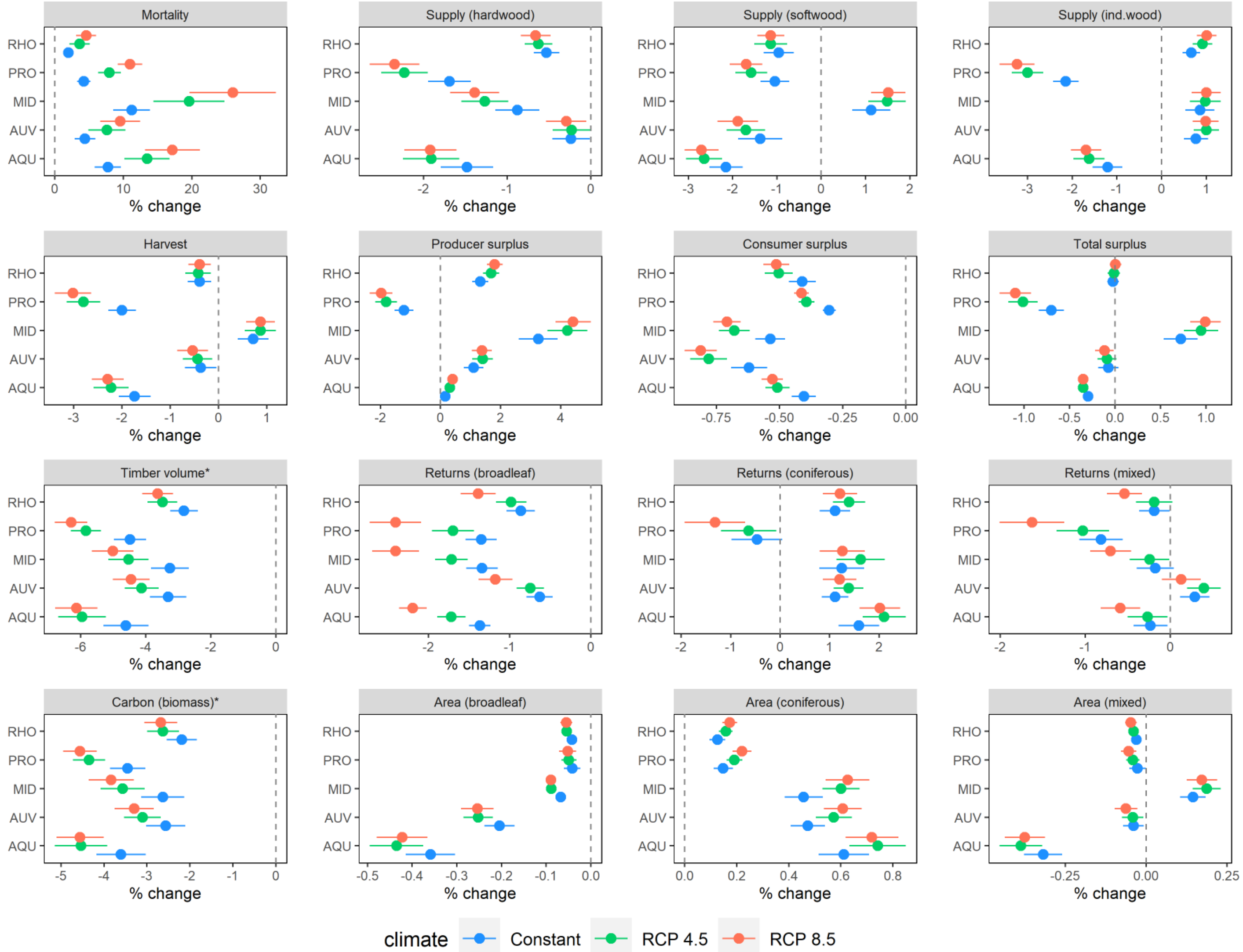
D.6. Producer surplus by product

Values are given as relative changes (%) against BAU (no fires) for the end of century period (2070-2100). Error bars indicate standard deviation across replications. Products are hardwood roundwood (hw), softwood roundwood (sw) and industrial wood (iw).

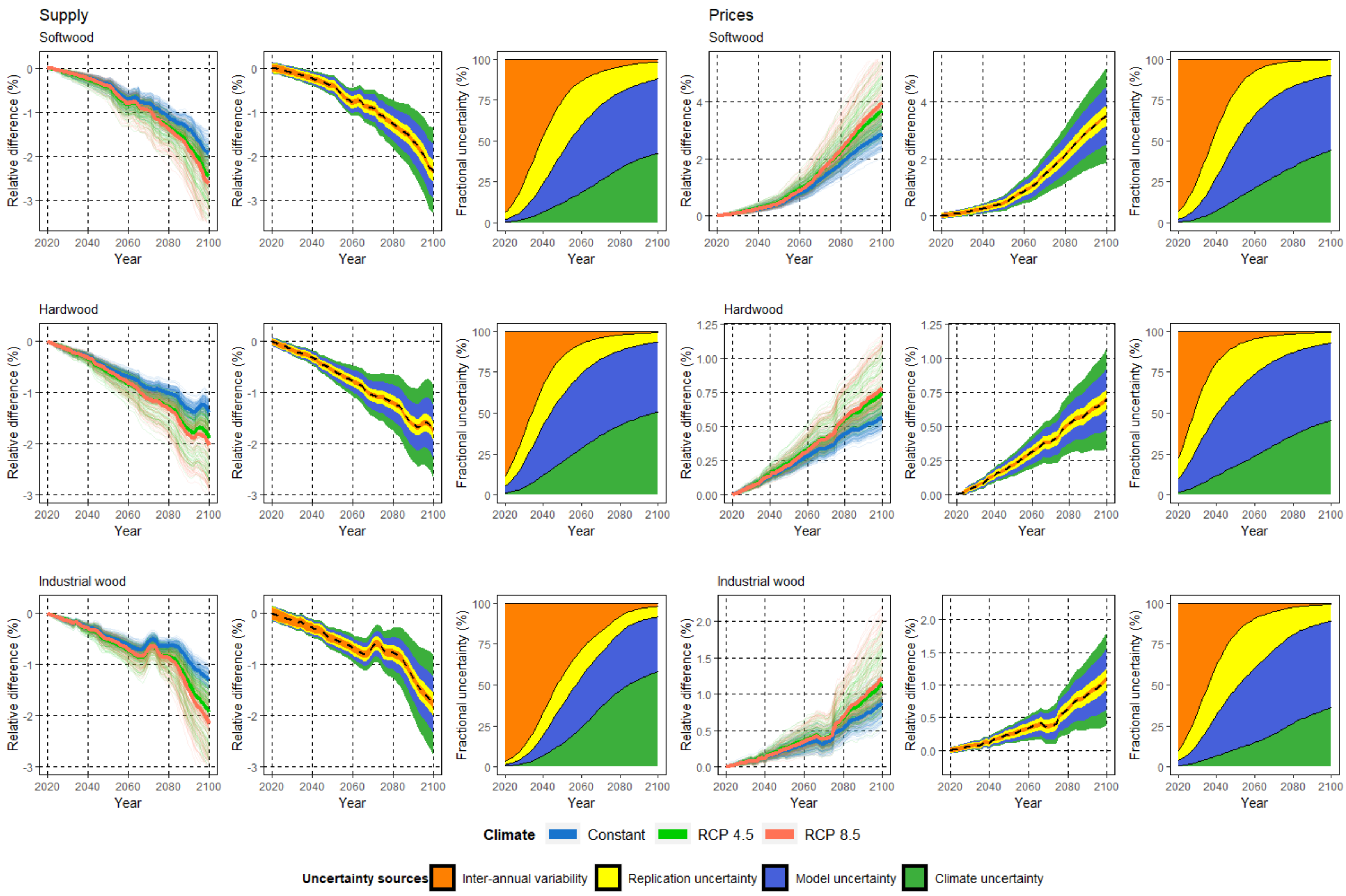


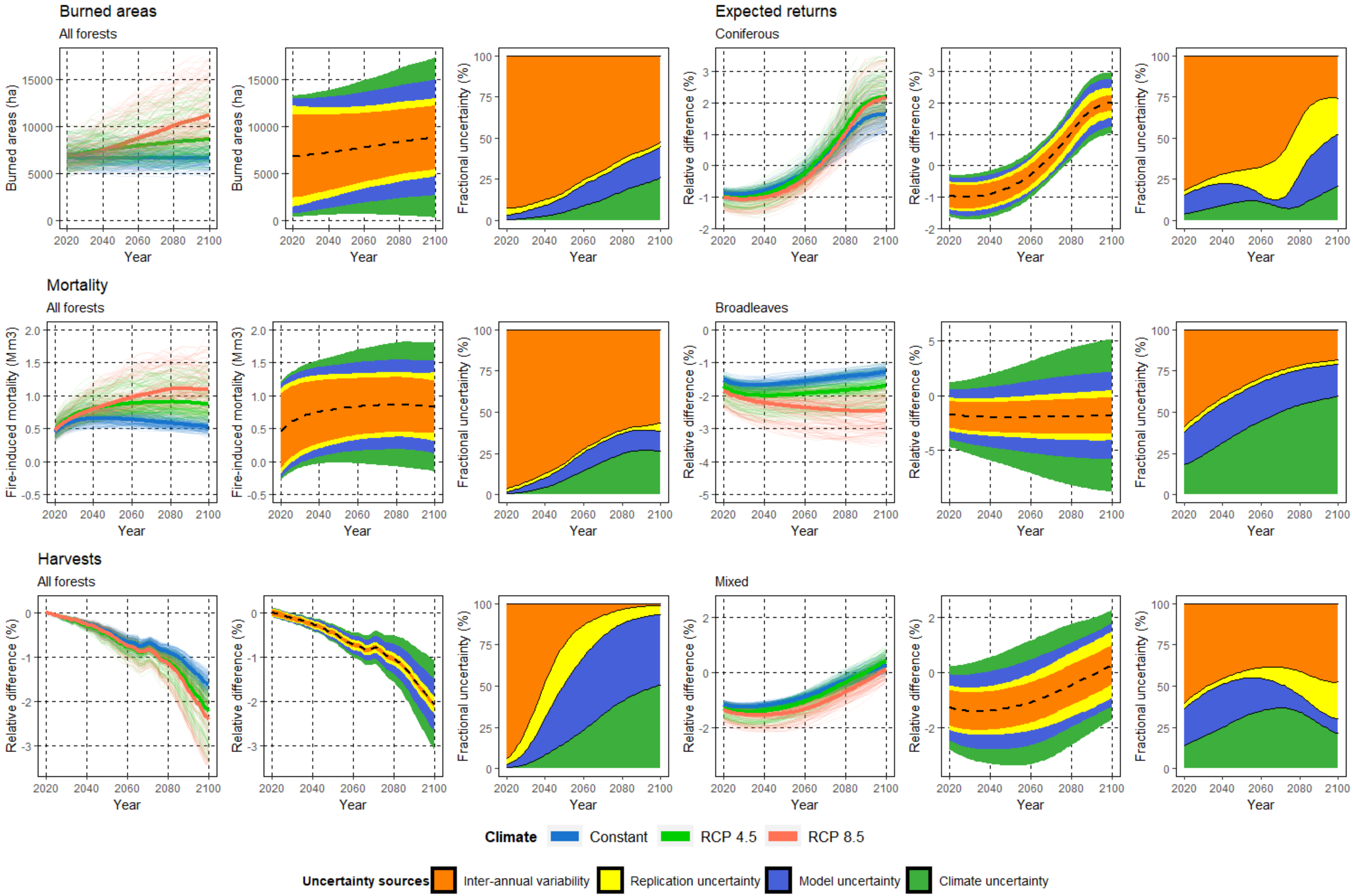
D.7. Numerical results disaggregated by region.

Values are given as relative changes (%) against BAU (no fires) for the end of century period (2070-2100) except for forest volumes, forest areas and carbon contents, where they are given for the last year of the simulation (2100). Error bars indicate standard deviation across replications.



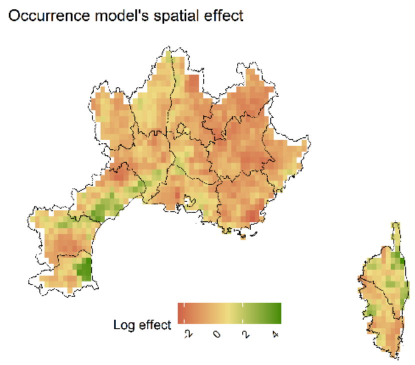
D.8. Uncertainty partitioning results for fire activity and forest sector dynamics.

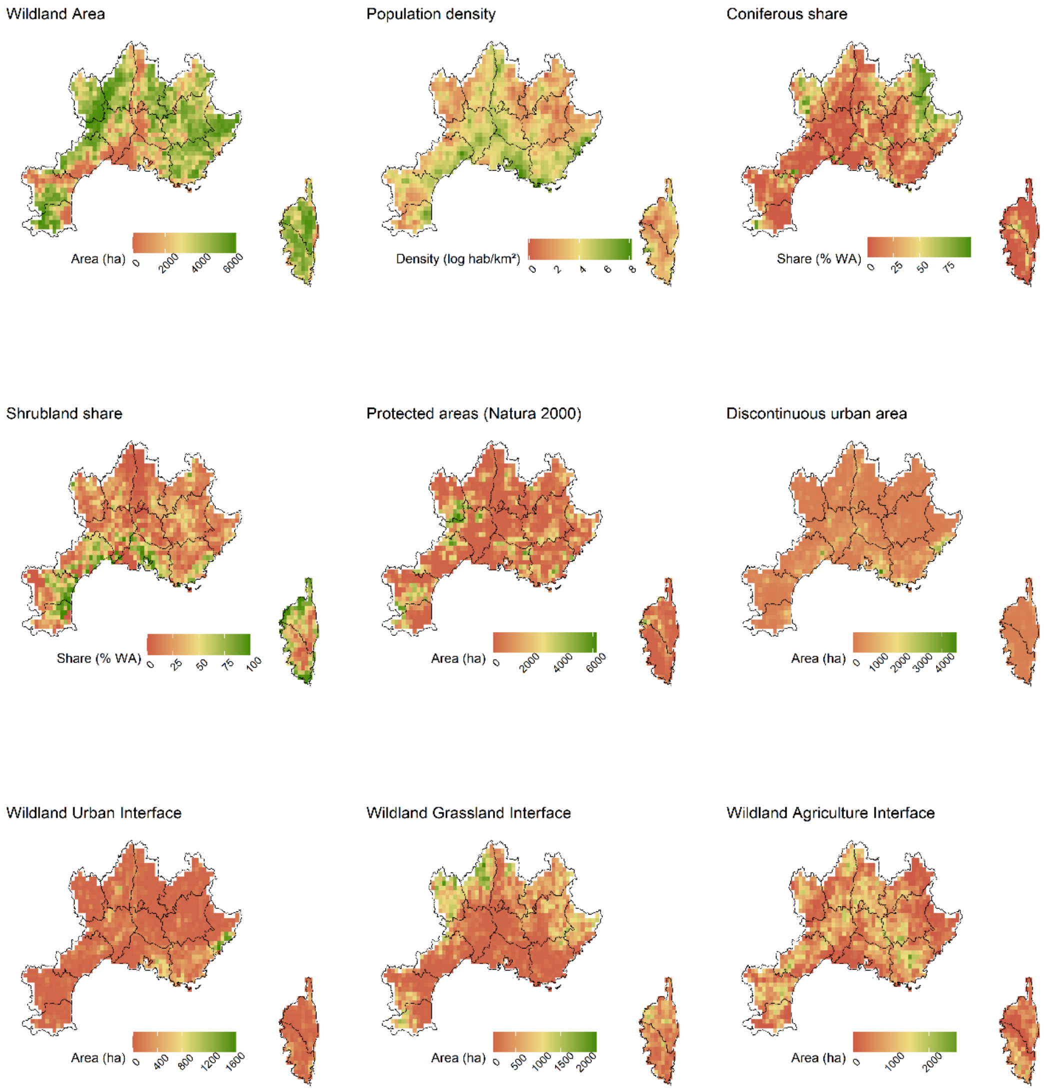



Burned areas
All forests
Burned areas (ha)
Fractional uncertainty (%)
Year
Expected returns
Coniferous
Relative difference (%)
Mortality
All forests
Fire-induced mortality (Mm3)
Broadleaves
Harvests
All forests
Mixed
Climate
Constant
RCP 4.5
RCP 8.5
Uncertainty sources
Inter-annual variability
Replication uncertainty
Model uncertainty
Climate uncertainty

D.9. Maps of the occurrence model's spatial effect and of LULC-SE predictors.

The first map represents the fire occurrence model's spatial effect (the dependent variable). In red pixels, the model tends to over-estimate fire count (negative correction), and in green pixels, it tends to underestimate fire count (positive correction). All other maps show the spatial distribution of predictor variables.





References

Armington, P. S. (1969) 'A Theory of Demand for Products Distinguished by Place of Production (Une theorie de la demande de produits differencies d'apres leur origine) (Una teoria de la demanda de productos distinguiendolos segun el lugar de produccion)', *Staff Papers - International Monetary Fund*. Palgrave Macmillan JournalsInternational Monetary Fund, 16(1), p. 159.

Buongiorno, J. (1996) 'Forest sector modeling: A synthesis of econometrics, mathematical programming, and system dynamics methods', *International Journal of Forecasting*, 12(3), pp. 329–343. doi: 10.1016/0169-2070(96)00668-1.

Catry, F. X. *et al.* (2010) 'Post-fire tree mortality in mixed forests of central Portugal', *Forest Ecology and Management*. Elsevier B.V., 260(7), pp. 1184–1192.

Catry, F. X. *et al.* (2013) 'Post-fire response variability in Mediterranean Basin tree species in Portugal', *International Journal of Wildland Fire*, 22(7), pp. 919–932. doi: 10.1071/WF12215.

Caurla, S. *et al.* (2010) *The French Forest Sector Model: version 1.0.*

Conedera, M. *et al.* (2010) 'Fire resistance and vegetative recruitment ability of different deciduous trees species after low-to moderate-intensity surface fires in southern Switzerland', *VI International Conference on Forest Fire Research*, (November 2015).

Dupire, S. *et al.* (2019) 'Vulnerability of forest ecosystems to fire in the French Alps', *European Journal of Forest Research*. Springer Berlin Heidelberg, 138(5), pp. 813–830.

Fargeon, H. *et al.* (2020) 'Projections of fire danger under climate change over France: where do the greatest uncertainties lie?', *Climatic Change*. Springer, 160(3), pp. 479–493.

Faustmann, M. (1849) 'Berechnung des wertes welchen Wladboden sowie noch nicht haubare Holzbestände für die Wladwirtschaft besitzen [Calculation of the value which forest land and immature stands possess for forestry]', *Allgemeine Forst- und Jadg-Zeitung*, 15, pp. 441–455.

Fernandes, P. M. *et al.* (2008a) 'Fire resistance of European pines', *Forest Ecology and Management*. Elsevier, pp. 246–255. doi: 10.1016/j.foreco.2008.04.032.

Fernandes, P. M. and Rigolot, E. (2007) 'The fire ecology and management of maritime pine (Pinus pinaster Ait.)', *Forest Ecology and Management*, 241(1–3), pp. 1–13.

Fréjaville, T. *et al.* (2018) 'Aridity and competition drive fire resistance trait covariation in mountain trees', *Ecosphere*, 9(12).

Fréjaville, T., Curt, T. and Carcaillet, C. (2018) 'Higher potential fire intensity at the dry range margins of European mountain trees', *Journal of Biogeography*, 45(9), pp. 2003–2015.

Garcia-Gonzalo, J. *et al.* (2011) 'A three-step approach to post-fire mortality modelling in maritime pine (Pinus pinaster Ait) stands for enhanced forest planning in Portugal', *Forestry*, 84(2), pp. 197–206.

Hood, S. M. *et al.* (2007) 'Evaluation of a post-fire tree mortality model for western USA conifers', *International Journal of Wildland Fire*. CSIRO PUBLISHING, 16(6), pp. 679–689.

Hood, S. M. *et al.* (2018) 'Fire and tree death: Understanding and improving modeling of fire-induced tree mortality', *Environmental Research Letters*.

Keeley, J. E. (2012) 'Ecology and evolution of pine life histories', *Annals of Forest Science*, pp. 445–453.

Kloster, S. *et al.* (2010) 'Fire dynamics during the 20th century simulated by the Community Land Model', *Biogeosciences*, 7(6), pp. 1877–1902.

Li, F., Zeng, X. D. and Levis, S. (2012) 'A process-based fire parameterization of intermediate complexity in a dynamic global vegetation model', *Biogeosciences*, 9(7), pp. 2761–2780.

Lobianco, A. *et al.* (2015) 'The importance of introducing spatial heterogeneity in bio-economic forest models: Insights gleaned from FFSM++', *Ecological Modelling*, 309–310, pp. 82–92.

Lobianco, A., Delacote, P., *et al.* (2016) 'Accounting for Active Management and Risk Attitude in Forest Sector Models An Impact Study on French Forests', *Environ Model Assess*, 21, pp. 391–405.

Lobianco, A., Caurla, S., *et al.* (2016) 'Carbon mitigation potential of the French forest sector under threat of combined physical and market impacts due to climate change', *Journal of Forest Economics*, 23, pp. 4–26.

Maringer, J. *et al.* (2016) 'What drives European beech (Fagus sylvatica L.) mortality after forest fires of varying severity?', *Forest Ecology and Management*. Elsevier B.V., 368, pp. 81–93.

Pimont, F. *et al.* (2014) 'Les effets du passage d'un feu dans un peuplement arboré. Synthèse des connaissances et applications pour le gestionnaire forestier méditerranéen', *Forêt Méditerranéenne*, XXXV(1), pp. 17–30.

Pimont F., Fargeon H., Opitz T., Ruffault J., Barbero R., Martin StPaul N., Rigolot E., Riviere M., Dupuy JL., in print. Prediction of regional wildfire activity in the probabilistic Bayesian framework of Firelihood. *Ecological Applications*.

Pimont, F., Prodon, R. and Rigolot, E. (2011) 'Comparison of postfire mortality in endemic Corsican black pine (Pinus nigra ssp. laricio) and its direct competitor (Pinus pinaster)', *Annals of Forest Science*, 68(2), pp. 425–432.

Rigolot, E. (2004) 'Predicting postfire mortality of Pinus halepensis Mill. and Pinus pinea L.', *Plant Ecology*, 171(1–2), pp. 139–151.

Ryan, K. and Amman, G. (1994) 'Interactions between fire-injured trees and insects in the Greater Yellowstone Area', *Plants and their Environments : Proceedings of the First Biennial Scientific Conference on the Greater Yellowstone Ecosystem*, pp. 259–271.

Samuelson, P. A. (1952) 'Spatial price equilibrium and linear programming', *American Economic Review*. American Economic Association, 42(3), pp. 283–303.

Sauquet, A. *et al.* (2011) 'Estimating Armington elasticities for sawnwood and application to the French Forest Sector Model', *Resource and Energy Economics*, 33, pp. 771–781..

Thonicke, K. *et al.* (2001) 'The role of fire disturbance for global vegetation dynamics: Coupling fire into a dynamic global vegetation model', *Global Ecology and Biogeography*. John Wiley & Sons, Ltd, 10(6), pp. 661–677.

Venevsky, S. *et al.* (2019) 'Analysis fire patterns and drivers with a global SEVER-FIRE v1.0 model incorporated into dynamic global vegetation model and satellite and on-ground observations', *Geoscientific Model Development*, 12(1), pp. 89–110.

Woolley, T. *et al.* (2012) 'A review of logistic regression models used to predict post-fire tree mortality of western North American conifers', *International Journal of Wildland Fire*, pp. 1–35.

L'analyse prospective dans le secteur forêt-bois face aux enjeux environnementaux: éclairages issus de la modélisation bioéconomique à grande échelle

Résumé étendu en Français

Mots-clés : forêt, modélisation, changement climatique, feux de forêt, bioéconomie.

Introduction

La 2e moitié du XXe siècle et le XXIe siècle sont caractérisés par une montée en puissance des problématiques environnementales et de durabilité, au premier rang desquelles le changement climatique et ses conséquences (IPCC, 2014), et la communauté internationale s'est fixé des objectifs ambitieux en termes d'atténuation de ces changements, mais aussi d'adaptation (Rogelj et al., 2018; UNFCCC, 2015). Au sein des secteurs mobilisés, celui de la forêt et du bois se situe dans une situation particulière. En effet, ce dernier est en mesure de participer aux efforts d'atténuation au travers de la séquestration du carbone en forêt, dans les produits, et via des effets de substitution énergétique et matérielle (Austin et al., 2020; Favero et al., 2020), mais il est aussi fortement impacté par les conséquences du changement climatique, tels que l'augmentation de la fréquence des évènements extrêmes (Keenan, 2015; Lindner et al., 2010), qui remettent potentiellement en question les objectifs fixés (Le Page et al., 2013). Le secteur est en outre important du point de vue économique (Li et al., 2019), constitue un marqueur fort de l'identité des territoires (Stedman, 2003) et est à l'origine de nombreux services écosystémiques autres que la production de bois et la régulation du climat (Brockerhoff et al., 2017): il se situe donc à la croisée d'enjeux socio-économiques, climatiques, et environnementaux au sens plus large.

En raison de cette capacité à contribuer aux transitions écologiques en cours, la filière forêt-bois est souvent mobilisée dans les politiques publiques, qu'il s'agisse des politiques forestières au sens strict (Ministry of Agriculture, 2016), mais aussi des politiques climatiques (Nabuurs et al., 2018), de commerce (Moiseyev et al., 2010), de développement ou de protection de la nature (European Commission, 2015). Etant donné les temps longs en vigueur dans le domaine forestier, et au vu de la complexité du système forêt-filière, la modélisation bioéconomique est souvent utilisée pour questionner l'avenir et informer la prise de décision. Nous entendons par modèle une représentation des faits et processus dans un système-cible du monde réel (Morgan and Knuuttila, 2012), ici le secteur forestier, et nous concentrons sur les modèles représentant à la fois les dynamiques naturelles en amont (la ressource forestière) et les processus technologiques et comportements en aval (la filière), i.e. des modèles bioéconomiques. Le secteur forestier peut s'appréhender à plusieurs échelles spatiales, allant de la parcelle à la filière dans son ensemble. Nous nous concentrons ici sur ce dernier cas, et sur les modèles de secteur forestier (MSF), i.e. des modèles de simulation numérique alliant modélisation de la ressource et de la filière à grande échelle (Latta et al., 2013) couramment utilisés pour réaliser des exercices de prospective, des études d'impact et des évaluations de politiques publiques, et dont les résultats sont souvent repris dans des rapports à destination des décideurs (Ohrel, 2019; Toppinen and Kuuluvainen, 2010).

A l'origine créés pour projeter l'évolution des marchés du bois (Adams and Haynes, 2007), les MSF sont aujourd'hui mobilisés de manière croissante pour traiter de questions environnementales (Latta et al., 2013). A ce titre, il semblerait qu'ils accompagnent la transition des politiques forestières vers ces dernières. Cependant, les modélisateurs et chercheurs développant et utilisant les MSF se heurtent à plusieurs obstacles. En effet, l'intégration d'enjeux liés aux défis environnementaux et à la durabilité requièrent l'utilisation de données environnementales, souvent spatialisées à une échelle fine, la représentation de nouveaux processus (production de bioénergie, pratiques de gestion orientées vers le climat) ou encore la prise en compte des incertitudes liés aux risques climatiques. Au vu de ces limitations, on peut se demander si la recherche utilisant les MSF se pose « les bonnes questions (i.e. celles vues comme importantes du point de vue des preneurs de décision ou de l'industrie), ou seulement celles pour lesquelles les méthodes et les données sont disponibles ? » (Toppinen and Kuuluvainen, 2010).

A partir de ce constat, nous cherchons à répondre à la question suivante : **dans quelle mesure les MSF et la recherche s'appuyant dessus sont-ils capables d'accompagner les politiques forestières dans leur transition vers des questions environnementales ?** Afin d'apporter des éléments de réponse, nous adoptons une démarche en deux temps. Dans un premier temps, nous adoptons un point de vue conceptuel « autour des modèles » et cherchons à mieux comprendre la manière dont les MSF contribuent à l'appui à la prise de décision, en général (chapitre 1) et puis de manière plus spécifique aux objectifs environnementaux (chapitre 2). Dans un second temps, nous cherchons à mettre en lumière des solutions permettant un meilleur traitement des questions environnementales dans les MSF : la considération des conditions environnementales locales et le couplage de modèles écologie-économie. Ces deux solutions techniques sont mises en œuvre sur des cas d'étude appliqués ayant pour périmètre la filière forêt-bois en France et ayant pour thématique deux aspects du changement climatique en forêt : l'atténuation (séquestration de carbone, chapitre 3) et l'adaptation (risque de feux de forêts, chapitre 4).

Chapitre 1: Representations of the forest sector in economic models (Riviere and Caurla, 2020a)

Les MSF ont été développés à la fin des années 1970 pour simuler les futurs marchés du bois, et ont depuis été couramment utilisés dans le cadre d'exercices de prospective à destination des décideurs publics ou des administrations forestières (Latta et al., 2013; Toppinen and Kuuluvainen, 2010). Afin de mieux comprendre l'articulation entre modèles et politiques forestières, nous partons du concept de modèles en tant que représentations d'un système-cible dans le monde réel et permettant de l'explorer de manière indirecte (Frigg and Nguyen, 2017; Morgan and Knuuttila, 2012). Nous cherchons alors à expliciter les déterminants de la représentation du secteur forestier dans les MSF, c'est-à-dire à mieux comprendre quels sont les phénomènes représentés, comment, et pour quelles raisons.

Sans entrer dans le débat sur l'ontologie des modèles, si ces derniers sont utilisés pour mieux comprendre leur cible, alors il est probable qu'il existe un certain degré de ressemblance entre les deux (Morgan and Knuuttila, 2012). Le secteur forestier peut être envisagé comme la synthèse d'un amont (la forêt et la gestion) et d'un aval (industries et marchés). Les modèles sont donc amenés à représenter des phénomènes de natures différentes : faits naturels, technologiques, comportements (Solberg, 1986), intégrés horizontalement et verticalement (Johnston and van Kooten, 2014). En conséquence, les MSF sont des modèles de grande taille, « intégrés » dans le sens où ils unissent des approches issues de plusieurs disciplines (Hamilton et al., 2015). Cependant, ils ne partagent pas tous la même cible de cœur, et la section du secteur forestier mise en avant est souvent corrélée aux caractéristiques des régions où les modèles sont développés. Les représentations passent aussi par le choix de méthodes: alors que la représentation des dynamiques naturelles repose fortement sur les données empiriques d'inventaire forestier, celle des dynamiques économiques fait plus souvent appel à la théorie (Faustmann, 1849; Samuelson, 1952). Les MSF constituent une « traduction » des modèles économétriques estimés par ailleurs (Toppinen and Kuuluvainen, 2010), qui cohabitent ici avec des règles de décision et des équations basées sur les procédés (Buongiorno, 1996). Le secteur forestier peut en outre être appréhendé à différentes échelles, du local au global : les MSF sont la plupart du temps des modèles spatialisés, et la représentation du transport occupe une place importante, même si elle se limite souvent au calcul de distances entre des points moyens fictifs. Finalement, la question du temps occupe aussi une place prépondérante : bien que différents paradigmes de modélisation coexistent (Sjølie et al., 2015) l'horizon considéré va de la décennie au siècle, et les MSF permettent la planification stratégique, parfois la planification tactique, mais rarement la planification opérationnelle (D'amours et al., 2008).

La représentation du secteur forestier est aussi fortement dépendante de l'histoire. Une 1ère « famille » de MSF s'est développée dans les années 1970 afin de remplacer les méthodes basées sur l'extrapolation de données passées, inopérantes suite aux ruptures observées à l'époque (Adams and Haynes, 2007). Basés sur une modélisation de l'équilibre spatial, cette 1ère famille de modèles émerge comme une synthèse entre économétrie, *activity analysis*, et dynamique des systèmes (Buongiorno, 1996), sous l'impulsion notamment du service forestier Américain et le l'IIASA en Europe (Kallio et al., 1987). Une 2nde famille de modèles trouve ses racines dans les travaux d'économie forestière classique d'une part (Faustmann, 1849), remis au goût du jour par Samuelson (1976), et dans les travaux sur l'économie des ressources naturelles d'autre part (Hotelling, 1931), sous l'impulsion de Ressources For the Future aux Etats-Unis (Sedjo and Lyon, 1990). La recherche dans les décennies suivantes s'est développée le long de ces 2 axes et autour des équipes de recherche originelles en Europe et aux USA : des mises à jour des modèles existants ont été réalisées (certains modèles sont toujours utilisés aujourd'hui, e.g. Favero et al., 2020) et de nouveaux modèles ont été développés à partir des anciens (e.g. Trømborg and Sjølie, 2011). Aujourd'hui, cette organisation de la recherche autour des axes historiques se retrouve dans les dynamiques de publication (Figure 1). Toutefois, la taille relativement modeste du champ de recherche a permis de nombreux échanges, et des contributions croisées sont souvent identifiables.

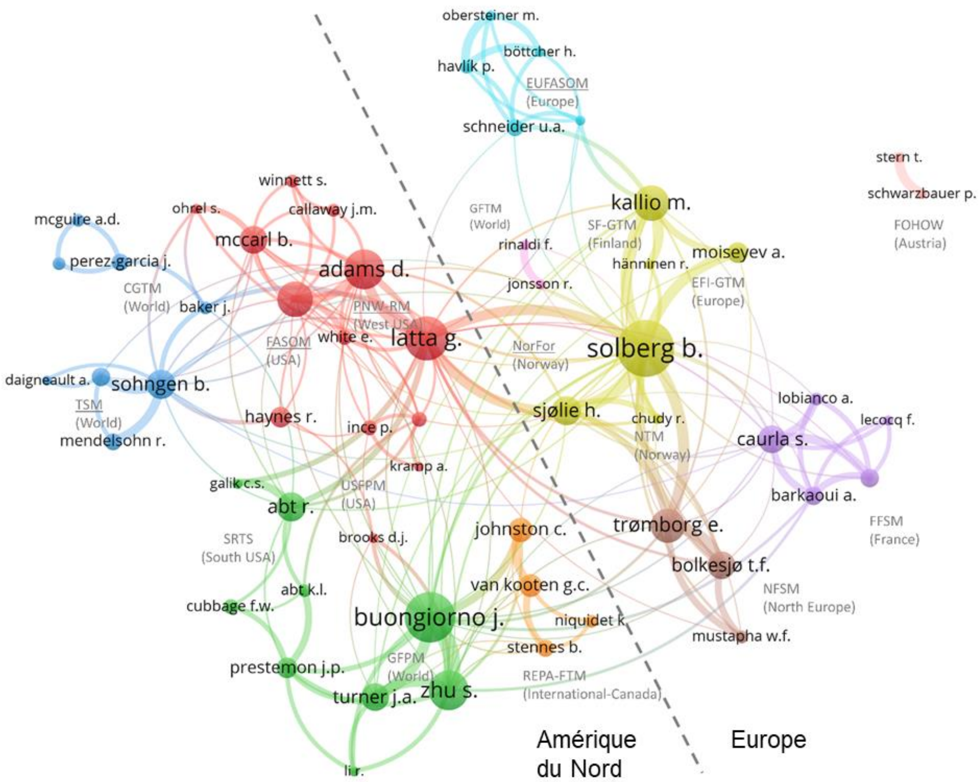


Figure 1 – Réseau et clusterisation des chercheurs dans le domaine de la modélisation bio-économique du secteur forestier, basé sur les données de co-citation. Les annotations et noms de modèles sont ajoutées par les auteurs. Les noms de modèles soulignés correspondent aux modèles d'optimisation inter-temporelle, les autres sont des modèles récursifs « myopes ».

Nous mobilisons finalement le schéma en 4 étapes de Morgan (2012) sur la manière dont les économistes interagissent avec les modèles afin de montrer que, bien que les MSF constituent un exemple classique de modélisation en économie, chaque étape est fortement influencée par leur utilisation pour l'appui à la décision. Les 2 premières étapes consistent à construire et questionner le modèle. Dans le cas des MSF, la question posée est, la plupart du temps, orientée par le débat public : elle prédate la création du modèle (Solberg, 1986) et son contenu dépend fortement de la teneur des débats contemporains de la création du modèle, e.g. la production d'énergie renouvelable depuis 15 ans (e.g. Bolkesjø et al., 2006), l'inclusion du secteur forestier dans la politique climatique de l'Union Européenne depuis quelques années (e.g. Solberg et al., 2019). Au-delà du contenu, la politique forestière influence également l'échelle à laquelle la question est abordée : énergie au niveau européen, climat au niveau mondial, industrie au niveau national. La question est ensuite explorée soit de manière positive (que se passera-t-il si la mesure est mise en place ?), soit de manière normative (quel est le chemin optimal pour atteindre l'objectif fixé ?). Le chercheur interagi alors de manière expérimentale avec son modèle, et puise dans les débats et documents politiques les informations nécessaires à la mise au point de récits narratifs, ensuite convertis en scénarios quantitatifs permettant de conduire des simulations. Il est ainsi courant de retrouver dans les variables d'entrée des modèles des grandeurs issues du débat politique, tels que des prix du carbone (Lecocq et al., 2011) ou des objectifs de production d'énergie (Galik et al., 2015). Les récits narratifs utilisés permettent en outre de relier les résultats de modélisation au monde réel, et de tirer des conclusions à propos de ce dernier à travers ce lien. Ces résultats ne se limitent cependant pas aux valeurs numériques, mais trouvent tout leur sens dans l'identification de tendances et la mise en lumière des mécanismes sous-jacents. Les MSF constituent donc des instruments d'exploration du « monde modélisé » (Morgan, 2012), étape préalable à la mise en place d'une recherche sur le système dans le monde réel par d'autres méthodes (Solberg, 1986). La principale exception à ce schéma concerne les études cherchant à répondre à une question portant sur le modèle lui-même (e.g. analyses de comportement dans Sjølie et al., 2015), mais qui, *in fine*, cherchent à améliorer l'éclairage fourni par les MSF pour la prise de décision. Par conséquent, nous identifions les politiques forestières comme étant le 3e déterminant majeur de la représentation du secteur forestier dans les modèles.

Chapitre 2 : Evolving integrated models from narrower economic tools: the example of forest sector models (Riviere et al., 2020).

Dans ce second chapitre, nous nous intéressons de manière plus particulière au traitement des questions environnementales avec les MSF, au travers du prisme des objectifs forestiers autres que la production de bois (*non-timber objectives*, NTO). Nous cherchons alors à identifier les NTO ayant été pris en compte dans les études prospectives avec les MSF, ainsi qu'à mettre en lumière les innovations techniques ayant permis leur intégration mais aussi les obstacles auxquels se heurte la recherche. Notre objectif est aussi de documenter les aspects ayant été investigués (les questions de recherche) afin d'identifier de potentiels angles morts.

Nous réalisons pour cela une revue systématique de la littérature sur le moteur de recherche Scopus, une analyse bibliométrique des résultats, une analyse en réseau des mots-clés utilisés, et terminons par une revue narrative d'articles sélectionnés. Cette procédure nous amène à constituer un corpus de 248 articles, au sein desquels nous identifions 197 articles d'analyse (Figure 2). Parmi ces derniers, 141 (72%) considèrent au moins un NTO, une proportion en forte augmentation sur la période 2010-2019 (figure 2). Nous identifions 5 NTO traités au sein des articles qui sont, par ordre d'importance : la production d'énergie renouvelable (59 articles), l'atténuation et l'adaptation au changement climatique (55), la préservation des habitats et de la biodiversité (22), la gestion des risques naturels (12) et la régulation de la ressource en eau (3). Les publications sont principalement concentrées dans deux revues spécialisées en économie forestière (*Journal of Forest Economics*, *Forest Policy and Economics*), puis dans des revues forestières généralistes (e.g. *Canadian Journal of Forest Research*). En revanche, les publications dans des revues d'économie plus générale ou de modélisation sont beaucoup plus rares, suggérant un certain isolement du champ de recherche. Ce dernier reste également polarisé autour des deux clusters où les FSM ont émergé dans les années 1980 : les Etats-Unis et l'Europe (Latta et al., 2013), alors que les pays du Sud sont notamment absents.

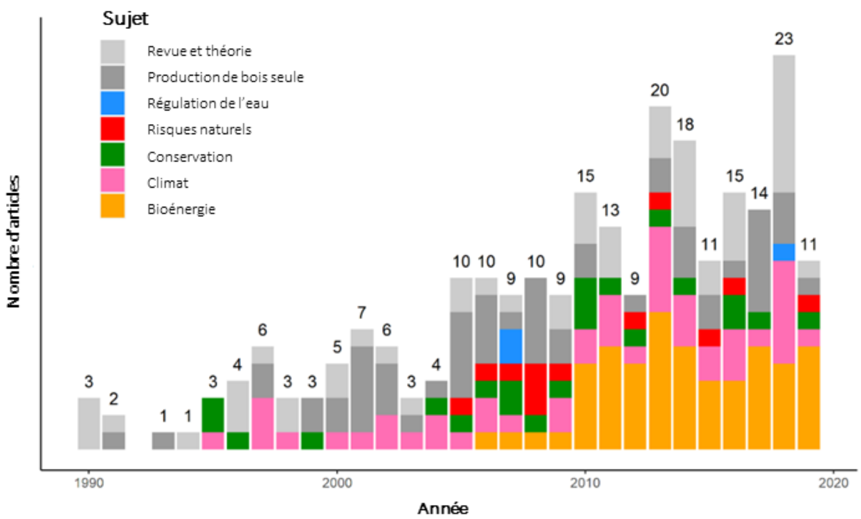


Figure 2 – Articles issus de la revue systématique de la littérature, et répartition par thématique

En ce qui concerne les mots-clés, on observe que la recherche se structure autour de deux axes : un axe amont-aval (Figure 3, clusters C et D et clusters A et B respectivement) et un axe production de bois (A et D) et régulation du climat (B et C). En termes de dynamique temporelle, la recherche s'est reportée dans les années récentes vers l'aval de la filière, les questions de marché, et la bioénergie (Figure 3b, Fgure 2).

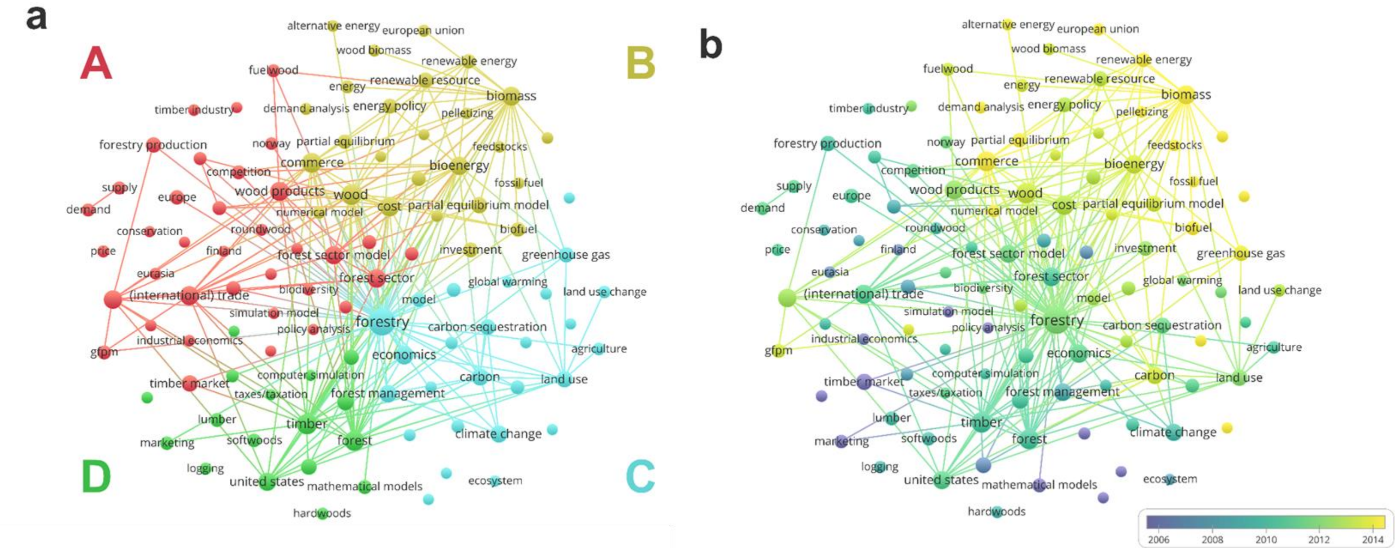


Figure 3 – Réseaux de mot-clés issus de la revue de littérature : clusters (a) et évolution temporelle (b).

L'inclusion des NTO dans les modèles nécessite de pouvoir les quantifier dans les modèles, et, les MSF étant des modèles d'optimisation, une intégration plus poussée nécessite la définition d'une nouvelle variable de décision. Notre exploration narrative des articles montre que cette intégration est inégale et incomplète selon les NTO considérés. Ceux étant plus proche de la cible originelle des modèles, par exemple la production de biomasse (proche de la production de bois) sont généralement intégrés de manière plus complète aux modèles (e.g. Bolkesjø et al., 2006). C'est également le cas pour la séquestration de carbone, dont l'intégration passe souvent par une valorisation de la tonne de carbone en unités monétaires, ce qui permet une inclusion dans la fonction objectif, un surplus économique. Les autres NTO sont quant à eux traités de manière plus superficielle, souvent quantifiés avec des proxies, et intégrés dans l'optimisation via des contraintes. Certains NTO n'ont pas été étudiés avec les MSF, notamment des services culturels (e.g. récréation) et de régulation (e.g. protection des sols). Nous identifions deux obstacles principaux à leur étude avec les MSF : la difficulté pour des modèles à grande échelle de prendre en charge des données spatialisées sur les conditions environnementales, et la difficulté d'estimer la valeur économique de ces services. Au final, les MSF semblent se spécialiser dans les questions d'énergie et de climat (Wear and Coulston, 2019), au détriment d'autres thématiques.

Nous identifions finalement deux solutions pour surmonter ces obstacles. La première consiste à développer des modèles multi-échelles ou des modèles à l'échelle régionale, ces derniers permettant de mieux prendre en compte l'hétérogénéité des contextes locaux et des comportements (e.g. Lobianco et al., 2015; Peter and Niquidet, 2016). La deuxième est la mise en place de couplages de modèles, notamment avec des modèles de simulation en sciences environnementales et permettant de représenter les dynamiques écologiques que les MSF ne peuvent pas prendre en charge, tels que la qualité des habitats forestiers pour la biodiversité ou les services de régulation de l'eau (Schleupner and Schneider, 2013; Yu et al., 2018).

Cependant, la mise en œuvre de ces solutions se heurte à des problématiques de complexité computationnelle, de multidisciplinarité, de cohérence des approches mobilisées, ou encore de disponibilité des données.

Chapitre 3 : Landscape implications of managing forests for carbon sequestration (Riviere and Caurla, 2020b)

La filière forêt-bois peut contribuer à l'atténuation du changement climatique via la séquestration de carbone en forêt (Sedjo and Sohngen, 2012). Afin de réaliser ce potentiel, les pratiques de gestion forestière doivent cependant être modifiées (Nabuurs et al., 2017), par exemple en augmentant les durées des révolutions, en changeant le timing des interventions, ou encore en changeant la composition ou la structure des peuplements (Adams et al., 2011; Austin et al., 2020; Sohngen and Brown, 2008). Sur le plan politique, la stimulation de cette « pompe à carbone » forestière est promue de manière croissante via des mécanismes de compensation carbone en forêt, volontaire ou dans le cadre d'une obligation réglementaire (Ecosystem Marketplace, 2017). Bien que ces questions aient été largement traitées en économie forestière classique à l'échelle de la parcelle (van Kooten and Johnston, 2016), la littérature à l'échelle sectorielle s'est focalisée sur la production de biomasse et les effets de substitution énergétique (e.g. Caurla et al., 2013; Moiseyev et al., 2011; White et al., 2013).

L'objectif de ce chapitre est d'évaluer les implications pour la filière bois et pour les paysages forestiers d'une gestion cherchant à la fois à produire du bois et à séquestrer du carbone *in situ*. Pour cela, nous utilisons le French Forest Sector Model (Lobianco et al., 2015), un MSF de la filière bois en France permettant de prendre en compte l'hétérogénéité des conditions environnementales sur le territoire à l'échelle de pixels géo-localisés de 8km. Nous y intégrons le modèle de rotations optimales de Hartman (1976) et van Kooten et al. (1995) pour les aménités autres que le bois, et utilisons la valeur de l'action pour le climat (Quinet, 2019) pour rendre compte de la contribution de la gestion forestière à l'atténuation du changement climatique, et réalisons des simulations pour la période 2020-2100.

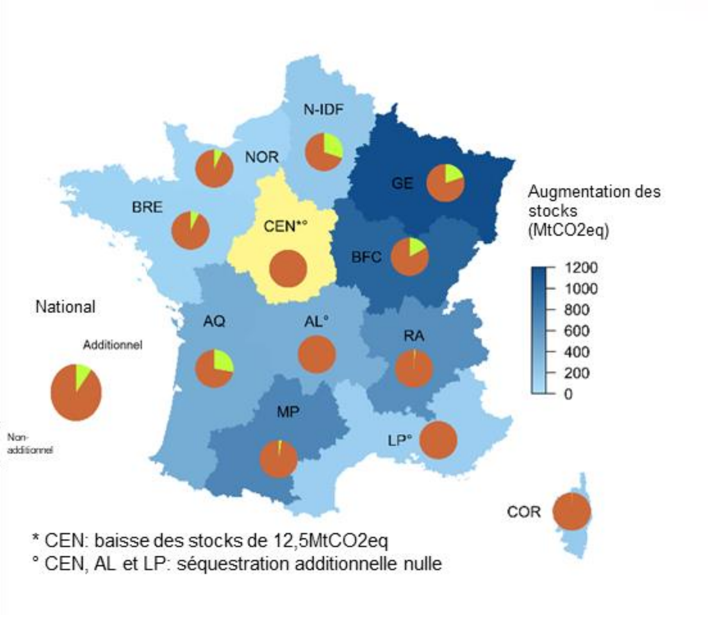


Figure 4 – Répartition régionale de la séquestration et de la séquestration additionnelle entre 2020 et 2100.

Nos résultats montrent que le potentiel de séquestration de la filière forêt-bois française peut être amélioré sur le court et le moyen terme en repoussant les récoltes, mais que ce dernier peut être amélioré sur le long terme en changeant la composition et la structure des forêts, pour un potentiel maximal de 500 MtC02eq d'ici à 2100. Cependant, ces potentiels sont inégalement répartis sur le territoire, et la séquestration additionnelle est principalement localisée dans les régions de l'Ouest et du Nord, alors qu'elle est particulièrement faible dans le Sud du pays (Figure 4). Sur le long terme, la composition des forêts évolue, et comporte une part plus importante de forêts feuillues et mélangées, ainsi que des forêts à structure intermédiaire, mais une fois de plus avec de fortes variations d'une région à l'autre (Figure 5). Ces évolutions peuvent à la fois présenter des co-bénéfices en termes de biodiversité par exemple, tout en se heurtant à de potentielles incompatibilités avec les politiques cherchant par exemple à augmenter les récoltes. Nos résultats montrent également que le contexte local (i.e. à l'intérieur de chaque région) est également un déterminant important des potentiels de séquestration, et nous mettons en évidence que les remplacements de conifères par des feuillus se limitent aux localités où les premiers présentent un potentiel de croissance limité.

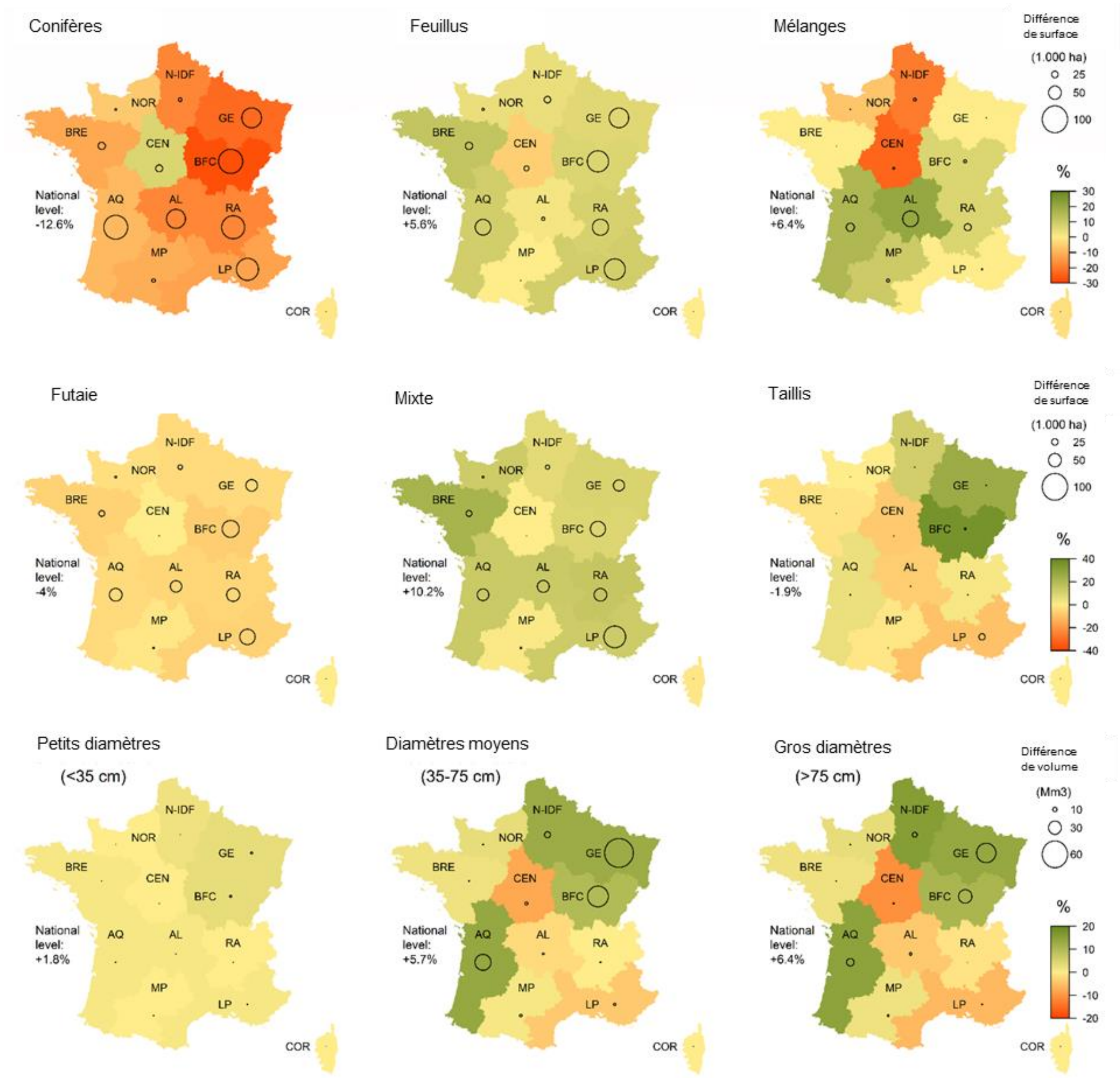


Figure 5 – Evolution des paysages forestiers de 2020 à 2100, en comparaison avec un scénario où la production de bois est le seul objectif. Composition (haut), structure verticale (milieu) et structure horizontale (bas).

En définitive, nos résultats suggèrent une approche régionalisée, voire locale, aux incitations à la séquestration de carbone en forêt. Ils questionnent également la séquestration de carbone dans la moitié Sud du pays, où les gains additionnels semblent faibles et où il est attendu que le risque de perturbations (incendies, pathogènes) et donc de non-permanence des stocks augmente sous l'influence du changement climatique (Lindner et al., 2010; Seidl et al., 2017).

Chapitre 4 : Forests under threat: assessing wildfire risk and climate-driven uncertainties in a large-scale forest model

Les feux de forêt affectent chaque année des centaines de milliers d'hectares de terres boisées dans le monde et, bien qu'ils fassent partie des processus écologiques naturels, ils peuvent avoir des conséquences négatives pour les activités économiques, les infrastructures et les biens, la santé, etc. (Bowman et al., 2020). Sous l'influence du changement climatique, il est attendu que les régimes de feux s'intensifient et gagnent de nouvelles régions, notamment en marge de la région méditerranéenne (Dupuy et al., 2020), remettant en question le potentiel d'atténuation de la filière bois via le relargage d'une partie du carbone séquestré (Seidl et al., 2014), mais aussi l'activité de la filière industrielle en aval. Les feux étant un phénomène stochastique dépendant fortement des conditions météorologiques et environnementales locales (Flannigan et al., 2009), leur appréhension à l'échelle sectorielle reste compliquée, notamment lorsque les modèles utilisés pour la recherche sont déterministes (Chudy et al., 2016).

L'objectif de ce chapitre est d'étudier les implications pour la filière bois d'une intensification des régimes de feux d'ici à la fin du siècle, mais aussi la propagation d'incertitudes du système climatique vers le secteur forêt-bois dans un modèle bioéconomique, et les conséquences pour les projections réalisées. Pour cela, nous utilisons un modèle probabiliste et spatialisé de l'activité des feux (Pimont et al., 2021) pour simuler ces derniers et propager l'incertitude climatique dans notre modèle de la filière bois, le FFSM (Lobianco et al., 2015). Nos simulations sont réalisées pour la moitié Sud de la France, sur la période 2020-2100, à partir de données issues de plusieurs modèles climatiques sous 3 niveaux de forçage radiatif (Figure 6). Nous réalisons 30 réplications (stochastiques) de chaque scénario, et réalisons une partition de l'incertitude en adaptant des méthodes issues des sciences du climat (Fargeon et al., 2020; Lehner et al., 2020).

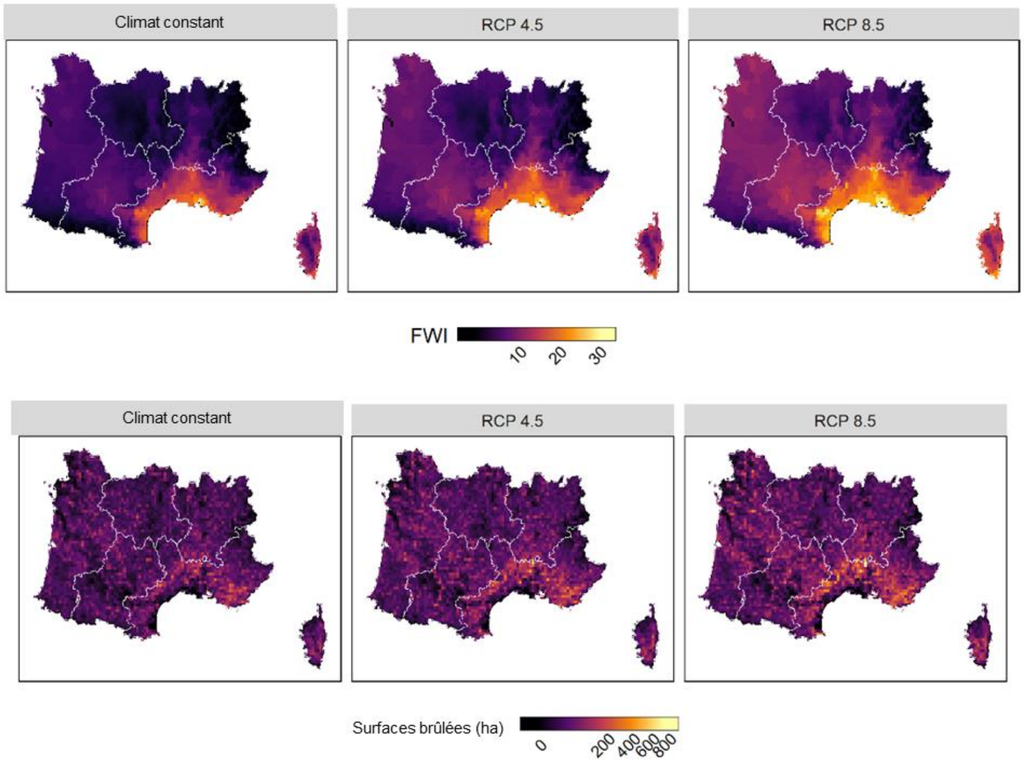


Figure 6 – Résultats de simulation moyens en période de fin de siècle (2070-2100) : indice forêt météo (FWI, haut) et surfaces brûlées (bas).

Nos résultats mettent en évidence une forte augmentation du danger et de l'aléa de feux d'ici à la fin du siècle, illustré par une augmentation du FWI, un indice de danger (Van Wagner, 1987), et des surfaces brûlées (Figure 6, haut et bas respectivement). Ces dernières augmentent particulièrement en Provence et dans le Languedoc, déjà très concernés aujourd'hui, mais également plus à l'Ouest, par exemple en Aquitaine. Les feux augmentent la mortalité en forêt jusqu'à 14%, provoquant des pertes d'inventaire et, en cascade, une baisse des récoltes et une augmentation des prix, en particulier pour la ressource résineuse, qui est répartie de manière hétérogène sur le territoire et plus exposée. Ces impacts restent cependant marginaux malgré l'augmentation des surfaces brûlées, et, pour les différentes grandeurs quantifiées, les différences entre le scénario en climat constant et les scénarios avec réchauffement (RCP 4.5 et 8.5) dépassent rarement 5%. La divergence entre les deux niveaux de forçage n'est d'ailleurs visible que dans la deuxième moitié du siècle. Cependant, les inventaires brûlés étant retirés de la production pour plusieurs décennies, ces impacts sont quasi-cumulatifs, et l'incertitude dans les projections augmente avec le temps (Figure 7, gauche).

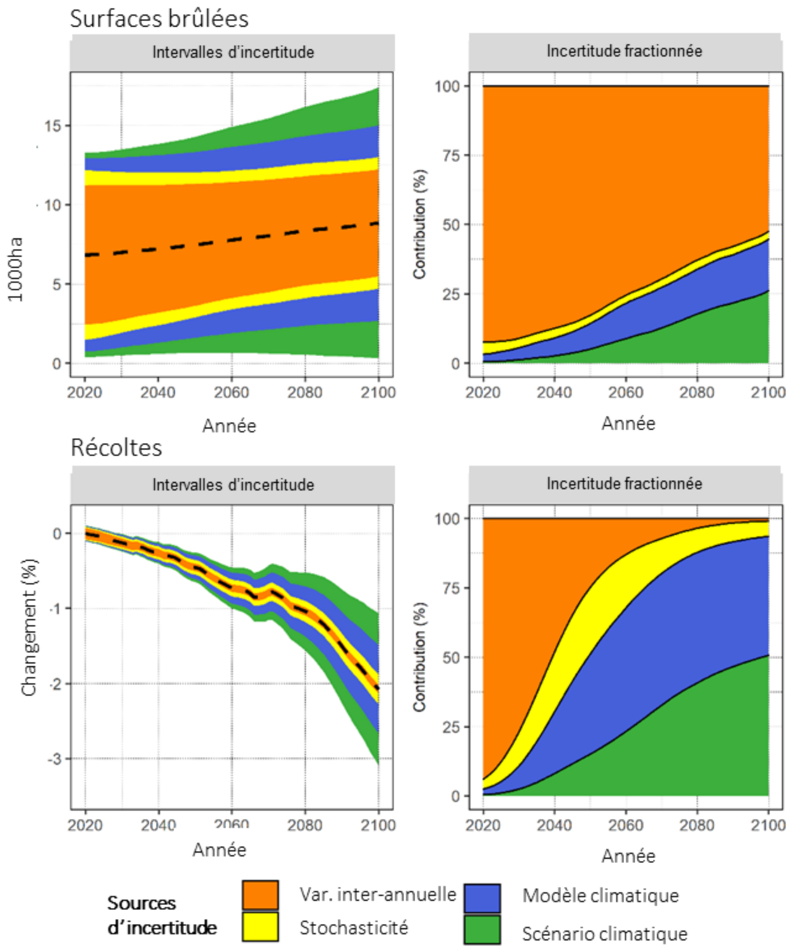


Figure 7 – Répartition des sources d'incertitude dans les résultats de simulation : activité des feux (surfaces brûlées, haut) et dynamiques dans la filière bois (récoltes, bas) ; intervalles d'incertitude (95%) autour de la prédiction moyenne (gauche) et contribution relative (droite).

Alors que l'activité des feux est dominée tout au long des simulations par une forte variabilité interannuelle (Figure 7, haut), cette dernière ne se propage que peu aux dynamiques de filière et sa contribution à l'incertitude totale est rapidement atténuée (Figure 7, bas). Sur le long terme, la contribution des incertitudes dues au choix du scénario et du modèle climatiques augmente, en particulier pour les dynamiques de filière. L'incertitude due à la variabilité inhérente au phénomène de feux représente un niveau stable et relativement important de l'incertitude totale pour les dynamiques dans la filière (5-35% selon les variables considérées), alors que sa contribution reste très modeste dans les projections de surfaces brûlées (<5%). Ces résultats confirment qu'il est important de prendre en compte plusieurs scénarios climatiques lors de la réalisation d'exercices de prospective sur le long terme, mais aussi qu'il peut être nécessaire d'aussi considérer la variabilité inhérente aux processus écologiques.

Bibliographie

Adams, D.M., Alig, R., Latta, G., White, E.M., 2011. Regional Impacts of a Program for Private Forest Carbon Offset Sales. J. For. 109, 444–461.

Adams, D.M., Haynes, R.W., 2007. Resource and market projections for forest policy development : twenty-five years of experience with the U.S. RPA timber assessment. Springer.

Austin, K.G., Baker, J.S., Sohngen, B.L., Wade, C.M., Daigneault, A., Ohrel, S.B., Ragnauth, S., Bean, A., 2020. The economic costs of planting, preserving, and managing the world's forests to mitigate climate change. Nat. Commun. 11, 1–9. https://doi.org/10.1038/s41467-020-19578-z

Bowman, D.M.J.S., Kolden, C.A., Abatzoglou, J.T., Johnston, F.H., van der Werf, G.R., Flannigan, M., 2020. Vegetation fires in the Anthropocene. Nat. Rev. Earth Environ. 1, 500–515. https://doi.org/10.1038/s43017-020-0085-3

Brockerhoff, E.G., Barbaro, L., Castagneyrol, B., Forrester, D.I., Gardiner, B., González-Olabarria, J.R., Lyver, P.O.B., Meurisse, N., Oxbrough, A., Taki, H., Thompson, I.D., van der Plas, F., Jactel, H., 2017. Forest biodiversity, ecosystem functioning and the provision of ecosystem services. Biodivers. Conserv. https://doi.org/10.1007/s10531-017-1453-2

Buongiorno, J., 1996. Forest sector modeling: A synthesis of econometrics, mathematical programming, and system dynamics methods. Int. J. Forecast. 12, 329–343. https://doi.org/10.1016/0169-2070(96)00668-1

Caurla, S., Delacote, P., Lecocq, F., Barkaoui, A., 2013. Stimulating fuelwood consumption through public policies: An assessment of economic and resource impacts based on the French Forest Sector Model. Energy Policy 63, 338–347. https://doi.org/10.1016/j.enpol.2013.07.111

Chudy, R.P., Sjølie, H.K., Solberg, B., 2016. Incorporating risk in forest sector modeling – state of the art and promising paths for future research. Scand. J. For. Res. 31, 719–727. https://doi.org/10.1080/02827581.2016.1212089

D'amours, S., Rönnqvist, M., Weintraub, A., 2008. Using Operational Research for supply chain planning in the forest products industry. INFOR 46, 265–281. https://doi.org/10.3138/infor.46.4.265

Dupuy, J., Fargeon, H., Martin-StPaul, N., Pimont, F., Ruffault, J., Guijarro, M., Hernando, C., Madrigal, J., Fernandes, P., 2020. Climate change impact on future wildfire danger and activity in southern Europe: a review. Ann. For. Sci. 77, 35. https://doi.org/10.1007/s13595-020-00933-5

Ecosystem Marketplace, 2017. Fertile ground, Fertile Ground State of Forest Carbon Finance 2017. Washington DC. https://doi.org/10.1002/asia.201200645

European Commission, 2015. Natura 2000 and Forests. Part I - II. Brussels. https://doi.org/10.2779/699873

Fargeon, H., Pimont, F., Martin-StPaul, N., De Caceres, M., Ruffault, J., Barbero, R., Dupuy, J.L., 2020. Projections of fire danger under climate change over France: where do the greatest uncertainties lie? Clim. Change 160, 479–493. https://doi.org/10.1007/s10584-019-02629-w

Faustmann, M., 1849. Berechnung des wertes welchen Wladboden sowie noch nicht haubare Holzbestände für die Wladwirtschaft besitzen [Calculation of the value which forest land and immature stands possess for forestry]. Allg. Forst- und Jadg-Zeitung 15, 441–455.

Favero, A., Daigneault, A., Sohngen, B., 2020. Forests: Carbon sequestration, biomass energy, or both? Sci. Adv. 6, eaay6792. https://doi.org/10.1126/sciadv.aay6792

Flannigan, M.D., Krawchuk, M.A., De Groot, W.J., Wotton, B.M., Gowman, L.M., 2009. Implications of changing climate for global wildland fire. Int. J. Wildl. Fire. https://doi.org/10.1071/WF08187

Folsland Bolkesjø, T., Trømborg, E., Solberg, B., 2006. Bioenergy from the forest sector: Economic potential and interactions with timber and forest products markets in Norway. Scand. J. For. Res. 21, 175–185. https://doi.org/10.1080/02827580600591216

Frigg, R., Nguyen, J., 2017. Models and Representation, in: Springer Handbooks. Springer, pp. 49–102. https://doi.org/10.1007/978-3-319-30526-4_3

Galik, C.S., Abt, R.C., Latta, G., Vegh, T., 2015. The environmental and economic effects of regional bioenergy policy in the southeastern U.S. Energy Policy 85, 335–346. https://doi.org/10.1016/j.enpol.2015.05.018

Hamilton, S.H., ElSawah, S., Guillaume, J.H.A., Jakeman, A.J., Pierce, S.A., 2015. Integrated assessment and modelling: Overview and synthesis ofsalient dimensions. Environ. Model. Softw. 64, 215–229. https://doi.org/10.1016/j.envsoft.2014.12.005

Hartman, R., 1976. The Harvesting Decision When A Standing Forest Has Value. Econ. Inq. XIV, 52–58. https://doi.org/10.1111/j.1465-7295.1976.tb00377.x

Hotelling, H., 1931. The Economics of Exhaustible Resources. J. Polit. Econ. 39, 137–175. https://doi.org/10.1086/254195

Intergovernmental Panel on Climate Change, 2014. Climate Change 2014 Synthesis Report - IPCC, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Gian-Kasper Plattner.

https://doi.org/10.1017/CBO9781107415324
Johnston, C., van Kooten, G.C., 2014. Modelling Bi-lateral Forest Product Trade Flows : Experiencing Vertical and Horizontal Chain.
Kallio, M., Dykstra, D.P., Binkley, C.S., 1987. The Global forest sector: an analytical perspective. Laxemburg. https://doi.org/10.1201/b16186
Keenan, R.J., 2015. Climate change impacts and adaptation in forest management: a review. Ann. For. Sci. 72, 145–167. https://doi.org/10.1007/s13595-014-0446-5
Latta, G.S., Sjolie, H.K., Solberg, B., 2013. A review of recent developments and applications of partial equilibrium models of the forest sector. J. For. Econ. 19, 350–360. https://doi.org/10.1016/j.jfe.2013.06.006
Le Page, Y., Hurtt, G., Thomson, A.M., Bond-Lamberty, B., Patel, P., Wise, M., Calvin, K., Kyle, P., Clarke, L., Edmonds, J., Janetos, A., 2013. Sensitivity of climate mitigation strategies to natural disturbances. Environ. Res. Lett. 8. https://doi.org/10.1088/1748-9326/8/1/015018
Lecocq, F., Caurla, S., Delacote, P., Barkaoui, A., Sauquet, A., 2011. Paying for forest carbon or stimulating fuelwood demand? Insights from the French Forest Sector Model. J. For. Econ. 17, 157–168. https://doi.org/10.1016/j.jfe.2011.02.011
Lehner, F., Deser, C., Maher, N., Marotzke, J., Fischer, E.M., Brunner, L., Knutti, R., Hawkins, E., 2020. Partitioning climate projection uncertainty with multiple large ensembles and CMIP5/6. Earth Syst. Dyn. 11, 491–508. https://doi.org/10.5194/esd-11-491-2020
Li, Y., Mei, B., Linhares-Juvenal, T., 2019. The economic contribution of the world's forest sector. For. Policy Econ. 100, 236–253. https://doi.org/10.1016/j.forpol.2019.01.004
Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., Lexer, M.J., Marchetti, M., 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. For. Ecol. Manage. 259, 698–709. https://doi.org/10.1016/j.foreco.2009.09.023
Lobianco, A., Delacote, P., Caurla, S., Barkaoui, A., 2015. The importance of introducing spatial heterogeneity in bio-economic forest models: Insights gleaned from FFSM++. Ecol. Modell. 309–310, 82–92. https://doi.org/10.1016/j.ecolmodel.2015.04.012
Ministry of Agriculture, A. and F., 2016. THE NATIONAL FOREST AND WOOD PROGRAMME (PNFB). Paris.
Moiseyev, A., Solberg, B., Kallio, A.M.I., Lindner, M., 2011. An economic analysis of the potential contribution of forest biomass to the EU RES target and its implications for the EU forest industries. J. For. Econ. 17, 197–213. https://doi.org/10.1016/j.jfe.2011.02.010
Moiseyev, A., Solberg, B., Michie, B., Kallio, A.M.I., 2010. Modeling the impacts of policy measures to prevent import of illegal wood and wood products. For. Policy Econ. 12, 24–30. https://doi.org/10.1016/j.forpol.2009.09.015
Morgan, M., 2012. The world in the model: How economists work and think.
Morgan, M.S., Knuuttila, T., 2012. Models and Modelling in Economics, in: Philosophy of Economics. pp. 49–87. https://doi.org/10.1016/B978-0-444-51676-3.50003-8
Nabuurs, G.-J., Arets, E.J.M.M., Schelhaas, M.-J., 2018. Understanding the implications of the EU-LULUCF regulation for the wood supply from EU forests to the EU. Carbon Balance Manag. 13, 18. https://doi.org/10.1186/s13021-018-0107-3
Nabuurs, G.-J., Delacote, P., Ellison, D., Hanewinkel, M., Hetemäki, L., Lindner, M., 2017. By 2050 the Mitigation Effects of EU Forests Could Nearly Double through Climate Smart Forestry. Forests 8, 484. https://doi.org/10.3390/f8120484
Ohrel, S.B., 2019. Policy perspective on the role of forest sector modeling. J. For. Econ. 34, 187–204. https://doi.org/10.1561/112.00000506
Peter, B., Niquidet, K., 2016. Estimates of residual fibre supply and the impacts of new bioenergy capacity from a forest sector transportation model of the Canadian Prairie Provinces. For. Policy Econ. 69, 62–72. https://doi.org/10.1016/j.forpol.2016.05.003
Pimont, F., Fargeon, H., Opitz, T., Ruffault, J., Barbero, R., Riviere, M., Dupuy, J.-L., 2021. Prediction of regional wildfire activity in the probabilistic Bayesian framework of Firelihood. Ecol. Appl.
Quinet, A., 2019. La valeur de l'action pour le climat Une valeur tutélaire du carbone pour évaluer les investissements et les politiques publiques Rapport de la commission présidée par.
Riviere, M., Caurla, S., 2020a. Representations of the Forest Sector in Economic Models. Oeconomia 0–28.
Riviere, M., Caurla, S., 2020b. Landscape implications of managing forests for carbon sequestration. For. An Int. J. For. Res. https://doi.org/10.1093/forestry/cpaa015
Riviere, M., Caurla, S., Delacote, P., 2020. Evolving Integrated Models From Narrower Economic Tools: the Example of Forest Sector Models. Environ. Model. Assess. https://doi.org/10.1007/s10666-020-09706-w
Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., Mundaca, L., Séférian, R., Vilariño, M., 2018. Mitigation Pathways Compatible with 1.5°C in

the Context of Sustainable Development, in: [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S.C., J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T.W. (eds. . (Eds.), Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change,. In press.
Samuelson, P.A., 1976. Economics of forestry in an evolving society. Econ. Enq. 14, 466–492. https://doi.org/10.4324/9781315182681-6
Samuelson, P.A., 1952. Spatial price equilibrium and linear programming. Am. Econ. Rev. 42, 283–303. https://doi.org/10.2307/1810381
Schleupner, C., Schneider, U.A., 2013. Allocation of European wetland restoration options for systematic conservation planning. Land use policy 30, 604–614. https://doi.org/10.1016/j.landusepol.2012.05.008
Sedjo, R.A., Lyon, K.S., 1990. The long-term adequacy of world timber supply.
Sedjo, R.A., Sohngen, B., 2012. Carbon Sequestration in Forests and Soils. Ssrn. https://doi.org/10.1146/annurev-resource-083110-115941
Seidl, R., Schelhaas, M.J., Rammer, W., Verkerk, P.J., 2014. Increasing forest disturbances in Europe and their impact on carbon storage. Nat. Clim. Chang. 4, 806–810. https://doi.org/10.1038/nclimate2318
Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M.J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T.A., Reyer, C.P.O., 2017. Forest disturbances under climate change. Nat. Clim. Chang. https://doi.org/10.1038/nclimate3303
Sjølie, H.K., Latta, G.S., Trømborg, E., Bolkesjø, T.F., Solberg, B., 2015. An assessment of forest sector modeling approaches: conceptual differences and quantitative comparison. Scand. J. For. Res. 30, 60–72. https://doi.org/10.1080/02827581.2014.999822
Sohngen, B., Brown, S., 2008. Extending timber rotations: Carbon and cost implications. Clim. Policy 8, 435–451. https://doi.org/10.3763/cpol.2007.0396
Solberg, B., 1986. Forest sector simulation models as methodological tools in forest policy analysis (Norway). Silva Fenn. 20, 419–427. https://doi.org/10.14214/sf.a27757
Solberg, B., Kallio, M.I., Käär, L., Päivinen, R., 2019. Grassi et al. miss their target. For. Policy Econ. https://doi.org/10.1016/j.forpol.2019.04.009
Stedman, R.C., 2003. Sense of Place and Forest Science: Toward a Program of Quantitative Research, in: Forest Science. Oxford Academic, pp. 822–829. https://doi.org/10.1093/forestscience/49.6.822
Toppinen, A., Kuuluvainen, J., 2010. Forest sector modelling in Europe-the state of the art and future research directions. For. Policy Econ. 12, 2–8. https://doi.org/10.1016/j.forpol.2009.09.017
Trømborg, E., Sjølie, H.K., 2011. Data applied in the forest sector models NorFor and NTMIII. Ina fagrapport. Dep. Ecol. Nat. Resour. Manag. Nor. Univ. Life Sci. 17.
UNFCCC, 2015. Paris Agreement, Conference of the Parties on its twenty-first session. https://doi.org/FCCC/CP/2015/L.9/Rev.1
van Kooten, G.C., Binkley, C.S., Delcourt, G., 1995. Effect of Carbon Taxes and Subsidies on Optimal Forest Rotation Age and Supply of Carbon Services. Am. J. Agric. Econ. 77, 365. https://doi.org/10.2307/1243546
van Kooten, G.C., Johnston, C., 2016. The Economics of Forest Carbon Offsets. Ssrn 1–20. https://doi.org/10.1146/annurev-resource-100815-095548
Van Wagner, C.E., 1987. Development and structure of the Canadian forest fire weather index system, Forestry. https://doi.org/19927
Wear, D.N., Coulston, J.W., 2019. Specifying Forest Sector Models for Forest Carbon Projections. J. For. Econ. 34, 73–97. https://doi.org/10.1561/112.00000443
White, E.M., Latta, G., Alig, R.J., Skog, K.E., Adams, D.M., 2013. Biomass production from the U.S. forest and agriculture sectors in support of a renewable electricity standard. Energy Policy 58, 64–74. https://doi.org/10.1016/j.enpol.2013.02.029
Yu, C.-H., McCarl, B., Yu, C.-H., McCarl, B.A., 2018. The Water Implications of Greenhouse Gas Mitigation: Effects on Land Use, Land Use Change, and Forestry. Sustainability 10, 2367. https://doi.org/10.3390/su10072367

Title: Prospective analysis in the forest sector when facing environmental challenges: insights from large-scale bioeconomic modelling

Keywords: forestry, modelling, climate change, wildfire, bioeconomy.

Abstract:

Forest policy increasingly mobilizes the forest sector to address environmental concerns. Owing to the forest sector's complexity and time scales involved, simulation models are often used as research methods to explore the future. This thesis investigates the contributions of Forest Sector Models (FSM), bio-economic simulation models commonly used for prospective analysis, to this transition.

We first adopt a conceptual perspective and, through a parallel exploration of the early literature in forest economics and the epistemology of model use, we show that forest policy has been, and still is, a strong driver of FSM research, influencing representation processes in models as well as narratives used to drive research. We also highlight that the nature of facts within the forest sector, the local context, data availability and past practices are other important determinants of model-based research. We subsequently review more recent literature to assess the extent to which environmental issues have been addressed. While originally focused on timber production and trade, a majority of the research now focuses on goals such as renewable energy production or the conservation of biodiversity. The treatment of such objectives has however been unequal, and those closer to the models' original target are treated more often and more deeply. On the contrary, modelling is hindered when economic values are hard to estimate or when models cannot handle spatialized data, hence objectives related to cultural and some regulation services are less commonly studied.

The remainder of the thesis addresses two aspects of climate change, namely mitigation and adaptation, and brings methodological contributions by leveraging two ways of overcoming obstacles to the investigation of environmental objectives with large-scale bio-economic models: model couplings and the consideration of local environmental conditions. Both chapters focus on France, where the diversity of local contexts makes analyses focused on the upstream forest sector relevant, and use the French Forest Sector Model (FFSM).

First, using the FFSM and Hartman's model for optimal rotations with non-timber amenities, we investigate consequences for forestry and landscapes of management practices aiming at both producing timber and sequestering carbon. We show that, while postponing harvests can increase carbon stocks in the short-term, changes in management regimes and species choice yield additional benefits in the long-term. Over time, these changes lead to more diverse forest landscapes in terms of composition and structure, with potential implications for policy and environmental co-benefits. However, trends show a high level of spatial variability across and within regions, highlighting the importance of considering the local context.

In-situ carbon stocks are however exposed to risks of non-permanence. We assess implications for the forest sector of climate-induced changes in wildfire regimes, as well as implications for model projections of uncertainties related to these changes. To do so, we use a probabilistic model of wildfire activity, which we couple to the FFSM, and we carry out multiple simulations using various radiative forcing levels and different climate models. Although locally significant, wildfires' impacts remain limited at the sectoral scale. Fires affect a limited amount of the resource every year but in a cumulative manner, and the influence of climate change is mostly witnessed in the latter half of the century. Inter-annual fluctuations in fire activity only marginally propagate to the forest sector, and most uncertainty comes from the choice of climate models and scenarios. Stochasticity in the fire process, although never predominant, accounts for a significant share of uncertainty. These results stress the importance of considering multiple possible outcomes and the inherent variability in environmental processes in large-scale model projections.

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Ecole Doctorale ABIES

Titre : L'analyse prospective dans le secteur forêt-bois face aux enjeux environnementaux: éclairages issus de la modélisation bioéconomique à grande échelle

Mots-clés : forêt, modélisation, changement climatique, feux de forêt, bioéconomie.

Résumé :

La politique forestière mobilise de manière croissante la filière forêt-bois pour contribuer à des objectifs d'ordre environnemental, et la modélisation est souvent utilisée comme moyen d'interroger le futur. Cette thèse explore la capacité des modèles de secteur forestier (MSF), des modèles de simulation bio-économiques, à accompagner cette transition.

Sur le plan conceptuel, nous explorons la littérature à l'origine des MSF ainsi que celle sur l'épistémologie des modèles économiques. Nous montrons que la politique forestière a été un déterminant fort des pratiques de recherche, influençant les représentations du secteur dans les modèles et les discours mobilisés pour conduire les simulations. Nous illustrons également l'influence d'autres facteurs: la nature des faits forestiers, le contexte local, la disponibilité de données et les pratiques passées. Nous nous intéressons ensuite aux évolutions récentes et montrons qu'alors que la production et le commerce du bois constituent les thématiques de recherche d'origine, les enjeux environnementaux tels que la production d'énergie renouvelable ou la protection des habitats sont aujourd'hui centraux. Leur intégration reste cependant inégale, et ils sont d'autant plus traités qu'ils se rapprochent des sujets originels. A l'inverse, en raison de la difficulté d'estimer une valeur économique ou de la formulation d'outils à une échelle inadaptée, la modélisation de certains services culturels et de régulation est plus difficile et superficielle.

Nous menons ensuite deux cas d'étude portant sur l'atténuation et l'adaptation au changement climatique et sur le secteur forestier Français, où la diversité des contextes locaux justifie de s'intéresser en détail à l'amont de la filière. Nous utilisons le French Forest Sector Model (FFSM) et cherchons à mettre en œuvre deux leviers méthodologiques susceptibles d'améliorer la prise en compte d'enjeux environnementaux: le couplage de modèles et la considération de l'hétérogénéité des conditions environnementales. Le FFSM est d'abord utilisé avec un modèle de rotations optimales incluant les aménités autres que le bois afin d'étudier les implications d'une gestion cherchant à séquestrer du carbone. Nous montrons que, sur le court terme, la séquestration est principalement améliorée en repoussant les récoltes. Sur le long terme, des bénéfices supplémentaires sont attendus en faisant évoluer la composition et la structure de la forêt, amenant à des paysages forestiers plus variés. Ces tendances présentent cependant une forte hétérogénéité spatiale entre et au sein des régions, soulignant l'importance de considérer le contexte local.

Le carbone *in situ* est cependant exposé à des risques de non-permanence. Nous évaluons les conséquences pour la filière forêt-bois de l'évolution des régimes de feux en contexte de changement climatique et les implications pour les projections des incertitudes liées à cette évolution. Nous utilisons un modèle probabiliste d'activité des feux que nous couplons au FFSM, et réalisons de multiples simulations pour plusieurs niveaux de forçage radiatif et modèles climatiques. Bien que localement importants, l'impact des feux reste limité à l'échelle de la filière. Ces derniers touchent une faible proportion de la ressource chaque année mais d'une manière cumulative, et leurs conséquences projetées sont particulièrement visibles dans la deuxième moitié du 21e siècle. Les variations interannuelles de l'activité des feux se propagent peu aux dynamiques de filière, et l'incertitude dans les projections provient principalement du choix du modèle et des scénarios climatiques. L'incertitude due à la stochasticité du phénomène de feux ne prédomine jamais mais représente une part significative de l'incertitude totale. Ces résultats soulignent l'importance de considérer de multiples scénarios ainsi que la variabilité inhérente aux processus écologiques dans la prospective utilisant des modèles bio-économiques à grande échelle.

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