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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.

Introduction

Reaching climate mitigation objectives requires immediate action (Masson-Delmotte *et al*., 2018), to which the forest sector can be an important contributor (Canadell and Raupach, 2008; Eriksson, 2015; Riahi et al., 2017; Tavoni et al., 2007). Wood-based products can substitute for more climate intensive materials to produce energy or to be used in construction (Birdsey et al., 2018; 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; Eriksson, 2015; Favero et al., 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; Englin and Callaway, 1995; Freedman et al., 2009; Gutrich and Howarth, 2007a; Im et al., 2007). Besides, sequestration potentials and costs vary across space, and incentives may induce different responses from forest owners (Adams et al., 2011; van Kooten et al., 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 economic modelling studies. Second, we outline the model used in this study and describe our scenarios. Third, we presents 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.

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 et al., 2013). In this field, a major focus has been on assessing the potential for producing bioenergy from forest biomass (Riviere et al., 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 et al., 2017; Favero and Mendelsohn, 2014; 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 (Gabriella Cevallos et al., 2019), including France (JORF, 2018). Forestry practices that increase carbon stocks and are eligible include avoided deforestation (e.g. 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 et al., 2016).

A few large-scale simulation experiments have focused on such incentives. Buongiorno & Zhu (2013) show that implementing offset payments at 50\$/tCO_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 *et al*., 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; Lintunen et al., 2016; van Kooten and Johnston, 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 French previous assessments (Caurla et al., 2013b; 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.

Material and methods

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., 2016b, 2015). The model comprises three modules (Figure 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).

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*., 2016b, 2015).

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 et al., 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:

$$LEV(T) = \frac{p_T q_T (1+r)^{-T} + \propto v_T P_c (1+r)^{-T} + \sum_{t=1}^{T} r P_c v_t (1+r)^{-t}}{1-(1+r)^{-T}} \quad (1),$$

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, $\sum_{t=1}^{T} rP_c v_t (1+r)^{-t}$ to the stream of yearly carbon rents, and $\propto v_T P_c (1+r)^{-T}$ 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.

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 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, which falls within the range recommended in the Stiglitz-Stern report on carbon pricing (High-Level Commission of Carbon Prices, 2017), while the HIGH scenario starts at 125€/tCO2eq.

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.

Results

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 1

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 payments lead to increases in *in situ* carbon stocks, as seen on Figure 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.

These trends hide significant regional differences. Figure 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.

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 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 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 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.

Management decisions

Table 2

Despite representing more than half of all investments, there is a strong decrease in investments in coniferous high forests, going from 68.1% of investments in BAU to 56.7% in MAIN (Table 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 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).

Table 3

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 2, Figure 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.

Long-term landscape implications

Over time, changes in harvesting and management decisions lead to changes in forest landscapes (Figure 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).

Discussion

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).

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 et al., 2009; Simonet et al., 2016).

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 et al., 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.

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 et al., 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 already 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 et al., 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 et al., 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 incentives directed at 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.

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.

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Supplementary material

The following supplementary material (SM) is available at Forestry online: SM 1 and 2 present results from Tables 1 and 2 at a more disaggregated level. SM 3 gives an overview of regional harvests and timber trade throughout the simulation. SM 4 gives an overview of the distribution of growth potentials for chosen forest types throughout the simulation. SM 5 shows relationships between additional carbon storage in each region, forest cover, harvest changes and growth dynamics. SM 6 gives an overview of investment decisions in each region. More information about the model, as well as model code, are available open-source at https://ffsm-project.org/wiki/en/home.

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Conflict of interest

None declared

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Table 1 - Market impacts. Values are reported as averages over the first and second half of the simulation, and changes are calculated against BAU.

Variable	Products	Period	BAU	MAIN-F		LOW		MAIN		HIGH	
Supply (Mm3)	*Hardwood roundwood*	2020-2060	5,44	5,4	(-0.68%)	5,41	(-0.53%)	5,4	(-0.68%)	5,4	(-0.8%)
		2061-2100	5,62	5,56	(-1.09%)	5,57	(-0.79%)	5,56	(-1.04%)	5,55	(-1.22%)
	Industrial wood	2020-2060	39,5	38,32	(-3.01%)	38,57	(-2.36%)	38,32	(-3.01%)	38,1	(-3.55%)
		2061-2100	40,78	38,71	(-5.07%)	39,23	(-3.81%)	38,75	(-4.97%)	38,41	(-5.8%)
	Softwood roundwood	2020-2060	21,39	21,32	(-0.33%)	21,33	(-0.27%)	21,32	(-0.34%)	21,31	(-0.4%)
		2061-2100	22,14	22,09	(-0.24%)	22,01	(-0.6%)	22	(-0.65%)	21,99	(-0.68%)
Prices (eur/m3)	*Hardwood roundwood*	2020-2060	101,75	107,67	(+5.82%)	106,4	(+4.57%)	107,66	(+5.8%)	108,73	(+6.86%)
		2061-2100	84,39	92,74	(+9.89%)	90,59	(+7.35%)	92,51	(+9.62%)	93,86	(+11.22%)
	Industrial wood	2020-2060	30,37	33,5	(+10.33%)	32,81	(+8.04%)	33,5	(+10.33%)	34,1	(+12.31%)
		2061-2100	27,1	31,68	(+16.9%)	30,56	(+12.74%)	31,68	(+16.89%)	32,5	(+19.92%)
	Softwood roundwood	2020-2060	75,21	76,5	(+1.71%)	76,24	(+1.36%)	76,53	(+1.74%)	76,76	+(2.05%)
		2061-2100	68,81	70,14	(+1.93%)	70,59	(+2.6%)	70,92	(+3.07%)	71,15	(+3.41%)
Exports (Mm3)	*Hardwood roundwood*	2020-2060	1,66	1,5	(-9.66%)	1,53	(-7.64%)	1,5	(-9.66%)	1,47	(-11.31%)
		2061-2100	2,27	1,97	(-13.43%)	2,04	(-10.34%)	1,97	(-13.32%)	1,92	(-15.34%)
	Industrial wood	2020-2060	3,43	2,78	(-18.85%)	2,91	(-15.1%)	2,78	(-18.84%)	2,68	(-21.81%)
		2061-2100	4,6	3,38	(-26.69%)	3,63	(-21.09%)	3,38	(-26.64%)	3,21	(-30.38%)
	Softwood roundwood	2020-2060	1,61	1,57	(-2.94%)	1,58	(-2.3%)	1,57	(-2.94%)	1,56	(-3.45%)
		2061-2100	1,86	1,8	(-3.19%)	1,81	(-2.5%)	1,8	(-3.24%)	1,79	(-3.75%)
Imports (Mm3)	*Transformed products*	2020-2060	8,82	8,87	(+0.59%)	8,86	(+0.46%)	8,87	(+0.59%)	8,88	(+0.7%)
		2061-2100	8,39	8,46	(+0.94%)	8,45	(+0.77%)	8,47	(+0.99%)	8,48	(+1.15%)
Producer surplus (Meur)	*Primary products*	2020-2060	1885	1941	(+2.95%)	1929	(+2.31%)	1941	(+2.96%)	1951,69	(+3.52%)
		2061-2100	1832	1891	(+3.24%)	1882	(+2.75%)	1897	(+3.57%)	1908,13	(+4.18%)
Consumer surplus (Meur)	*Transformed products*	2020-2060	6101	6022	(-1.3%)	6038	(-1.02%)	6021	(-1.3%)	6006,91	(-1.54%)
		2061-2100	6207	6082	(-2.03%)	6103	(-1.68%)	6074	(-2.15%)	6053,41	(-2.48%)

Table 2 - Harvest levels and post-harvesting management decisions, for each forest type. Changes are averaged over the simulation, and reported against BAU.

Variable	Forest type	BAU	MAIN-F		LOW		MAIN		HIGH	
Harvest volume (Mm3)	*All*	47.33	45.09	(-4.7%)	45.53	(-3.8%)	45.04	(-4.8%)	44.68	(-5.6%)
	Broadl. High Forest	10.58	9.66	(-8.7%)	9.86	(-6.8%)	9.66	(-8.7%)	9.5	(-10.2%)
	Mixed High Forest	2.84	2.61	(-8%)	2.66	(-6.2%)	2.62	(-7.9%)	2.58	(-9.2%)
	Conif. High Forest	20.16	19.92	(-1.2%)	19.87	(-1.4%)	19.83	(-1.7%)	19.79	(-1.8%)
	Broadl. Interm. Str.	9.56	8.81	(-7.9%)	9.02	(-5.7%)	8.85	(-7.5%)	8.72	(-8.8%)
	Mixed Interm. Str.	2.02	2.01	(-0.7%)	2.02	(-0.3%)	2.02	(-0.3%)	2.02	(-0.3%)
	Coppice	2.16	2.08	(-3.8%)	2.09	(-3.1%)	2.08	(-3.9%)	2.07	(-4.4%)
Share of investments	*Broadl. High Forest*	9.12%	8.81%	(-0.3)	8.86%	(-0.3)	8.82%	(-0.3)	8.81%	(-0.3)
	Mixed High Forest	8.45%	8.84%	(+0.4)	11.46%	(+3)	11.52%	(+3.1)	11.56%	(+3.1)
	Conif. High Forest	68.29%	68.14%	(-0.1)	57.15%	(-11.1)	56.98%	(-11.3)	56.89%	(-11.4)
	Broadl. Interm. Str.	8.38%	8.46%	(+0.1)	17.01%	(+8.6)	17.13%	(+8.8)	17.18%	(+8.8)
	Mixed Interm. Str.	4.9%	4.85%	(-0.1)	4.99%	(0.1)	5.01%	(+0.1)	5.01%	(0.1)
	Coppice	0.87%	0.9%	(0)	0.54%	(-0.3)	0.53%	(-0.3)	0.53%	(-0.3)
Expected rotation times¹ (years)	*All*	129.95	129.03	(-0.7%)	209.57	(+61.3%)	210.05	(+61.6%)	212.01	(+63.1%)
	Broadl. High Forest	142.85	141.06	(-1.3%)	227.95	(+59.6%)	227.39	(+59.2%)	232.06	(+62.4%)
	Mixed High Forest	111.39	110.6	(-0.7%)	216.93	(+94.8%)	218.7	(+96.3%)	219.94	(+97.5%)
	Conif. High Forest	96.21	96.14	(-0.1%)	230.8	(+139.9%)	232.27	(+141.4%)	233.45	(+142.7%)
	Broadl. Interm. Str.	143.37	141.92	(-1%)	243.71	(+70%)	245.06	+(70.9%)	245.93	(+71.5%)
	Mixed Interm. Str.	119.1	118.61	(-0.4%)	170.66	(+43.3%)	171.63	(+44.1%)	171.83	(+44.3%)
	Coppice	166.81	165.87	(-0.6%)	167.34	(0.3%)	165.27	(-0.9%)	168.82	(+1.2%)
Expected returns from timber¹ (eur/ha)	*All*	89.43	92.13	(+3%)	8.3	(-90.7%)	7.45	(-91.7%)	6.74	(-92.5%)
	Broadl. High Forest	61.56	65.91	(+7.1%)	4.5	(-92.7%)	4.16	(-93.2%)	3.96	(-93.6%)
	Mixed High Forest	86.38	91.11	(+5.5%)	7.73	(-91.1%)	6.79	(-92.1%)	6.17	(-92.9%)
	Conif. High Forest	110.09	112.3	(+2%)	10.8	(-90.2%)	9.66	(-91.2%)	8.58	(-92.2%)
	Broadl. Interm. Str.	59.81	63.9	(+6.8%)	3.46	(-94.2%)	3.19	(-94.7%)	3.06	(-94.9%)
	Mixed Interm. Str.	62.2	63.37	(+1.9%)	10.84	(-82.6%)	9.97	(-84%)	9.63	(-84.5%)
	Coppice	5.76	6.59	(+14.4%)	0.68	(-88.3%)	0.47	(-91.8%)	0.25	(-95.7%)
Growth multiplier²	*All*	0.83	0.83	(-0.4%)	0.77	(-8.3%)	0.76	(-8.4%)	0.76	(-8.3%)
	Broadl. High Forest	0.79	0.78	(-1%)	0.63	(-19.3%)	0.63	(-19.6%)	0.64	(-19%)
	Mixed High Forest	0.69	0.69	(-0.1%)	0.66	(-4.5%)	0.66	(-4.5%)	0.66	(-4.4%)
	Conif. High Forest	0.89	0.89	(-0.2%)	0.85	(-4%)	0.85	(-4.1%)	0.85	(-4.1%)
	Broadl. Interm. Str.	0.77	0.77	(-0.7%)	0.75	(-2.9%)	0.75	(-2.9%)	0.75	(-2.9%)
	Mixed Interm. Str.	0.72	0.72	(-0.3%)	0.55	(-23.2%)	0.55	(-23.2%)	0.55	(-23.1%)
	Coppice	0.96	0.95	(-0.5%)	0.52	(-45.5%)	0.52	(-45.7%)	0.52	(-45.3%)
Cover change (% area harvested)	*All*	39.99%	39.77%	(-0.2)	58.93%	(+18.9)	59.2%	(+19.2)	59.34%	(+19.4)
	Broadl. High Forest	68%	68.48%	(+0.5)	84.01%	(+16)	84.33%	(+16.3)	84.53%	(+16.5)
	Mixed High Forest	60.28%	58.74%	(-1.5)	78.6%	(+18.3)	78.64%	(+18.4)	78.67%	(+18.4)
	Conif. High Forest	11.64%	12.4%	(+0.8)	35.39%	(+23.7)	35.89%	(+24.3)	36.18%	(+24.5)
	Broadl. Interm. Str.	65.9%	65.71%	(-0.2)	73.48%	(+7.6)	73.73%	(+7.8)	73.95%	(+8.1)
	Mixed Interm. Str.	55.48%	55.81%	(+0.3)	81.45%	(+26)	81.73%	(+26.2)	81.87%	(+26.4)
	Coppice	74.39%	73.88%	(-0.5)	98.22%	(+23.8)	98.29%	(+23.9)	98.34%	(+23.9)

1 - Rotation lengths and timber revenues are expected values at the moment the decision is made (after harvest).

2 – Growth potential is reported as the growth multipliers associated to newly established forests in the model. A multiplier of 1 indicates growth speed equal to the regional average, and multipliers under 1 growth faster than the regional 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).

Table 3 – Average growth multipliers 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)

Note: 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.

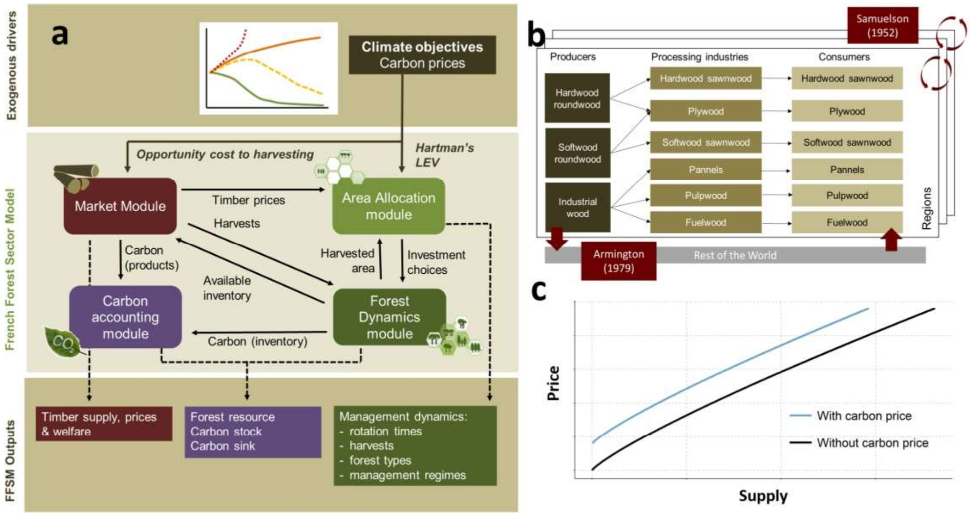
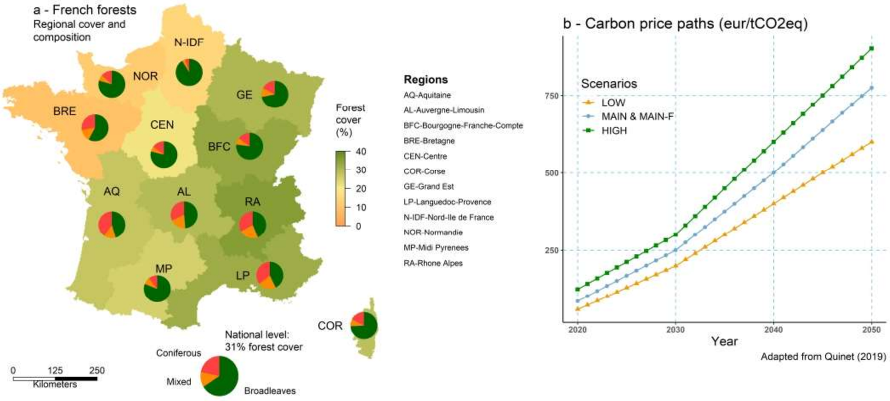


Figure 1 – Overview of the French Forest Sector Model. (a) General model structure and drivers for the current study. (b) Timber products in the market module. (c) Illustration of a supply shift. More detail about the model is available at https://ffsm-project.org/wiki/en/home.



a - French forests

Regional cover and composition

b - Carbon price paths (eur/tCO2eq)

Adapted from Quinet (2019)

Figure 2 – Illustration of the study case: (a) overview of French forests in the FFSM, (b) carbon price paths used in the simulations.

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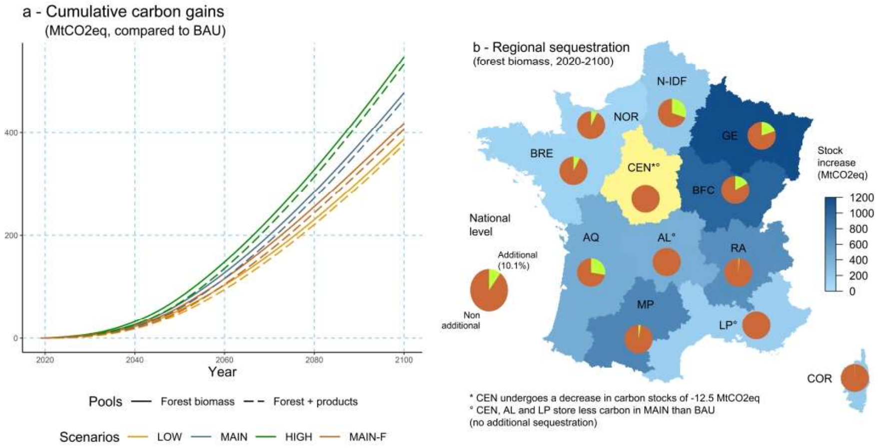

Figure 3 - Carbon dynamics at the national and regional levels: (a) cumulative carbon gains compared to BAU, (b) regional sequestration dynamics from 2020 to 2100 in MAIN.

1587x740mm (96 x 96 DPI)

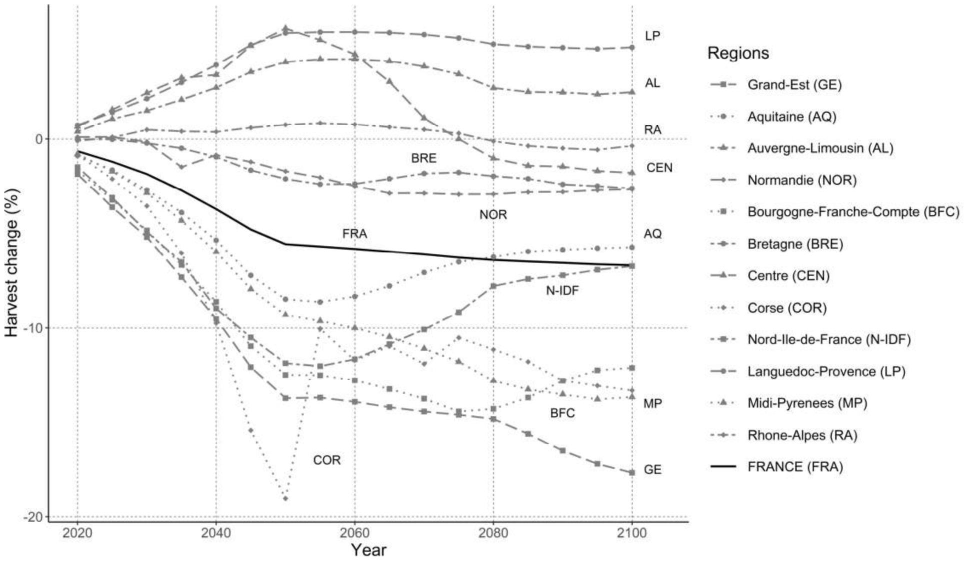

Figure 4 - Evolution of regional and national harvest levels in MAIN. Results are reported as percent changes against BAU over 5-year periods.

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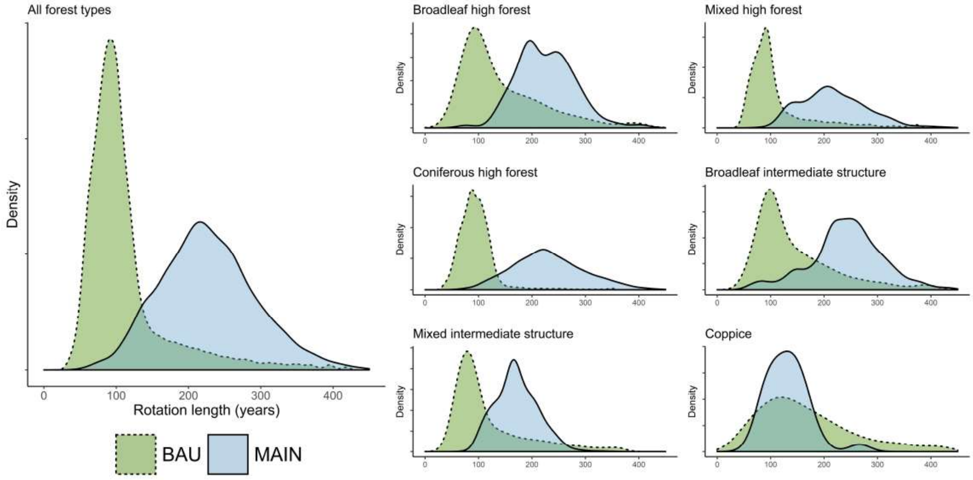

Figure 5 – Distribution of expected rotation lengths in MAIN and BAU. Values encompass all decisions taken throughout the simulations.

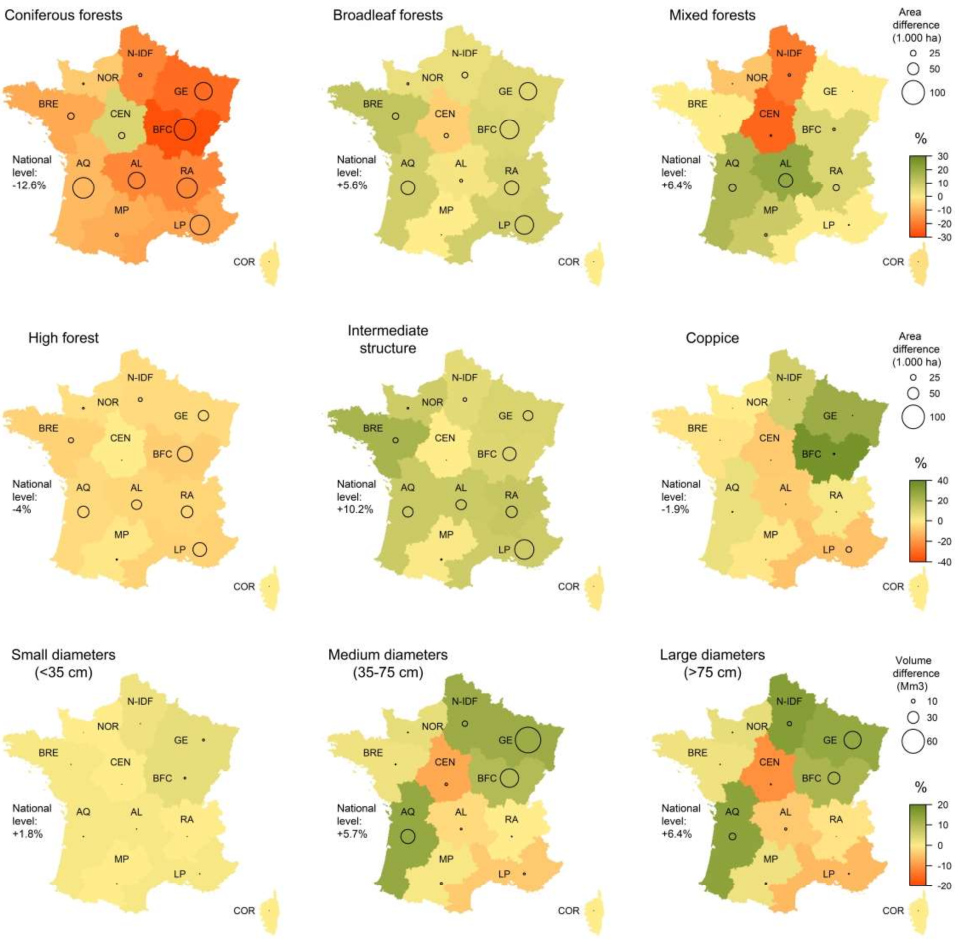

Figure 6 – Structure and composition of French forests in 2100 in MAIN compared to BAU. Circle size indicates absolute differences in areas or volumes, colours indicate relative differences.

1587x1587mm (96 x 96 DPI)

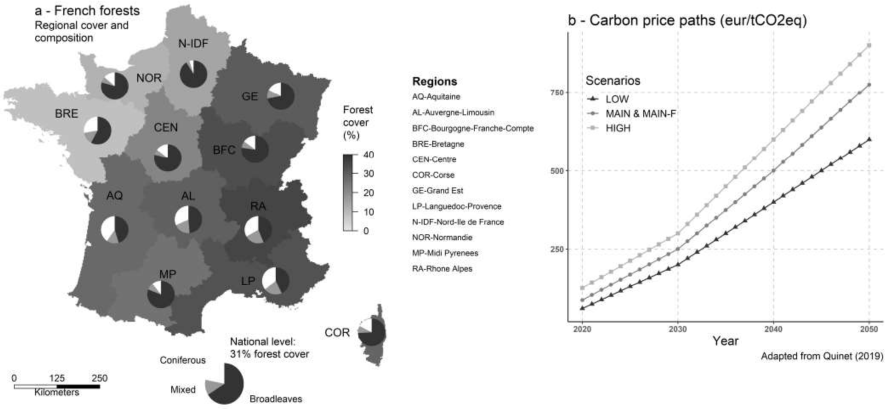

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Figure 2 – Illustration of the study case: (a) overview of French forests in the FFSM, (b) carbon price paths used in the simulations.

1587x778mm (96 x 96 DPI)

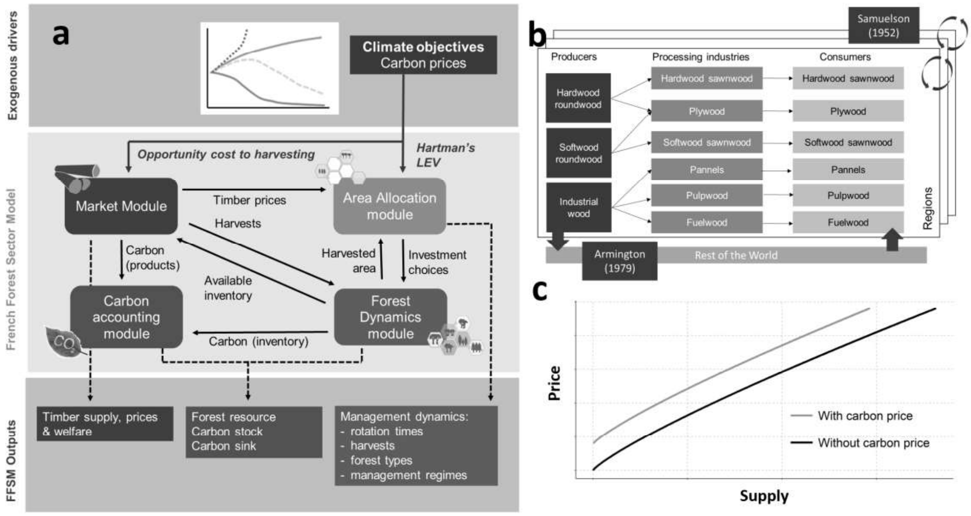


Figure 1 – Overview of the French Forest Sector Model. (a) General model structure and drivers for the current study. (b) Timber products in the market module. (c) Illustration of a supply shift. More detail about the model is available at https://ffsm-project.org/wiki/en/home.

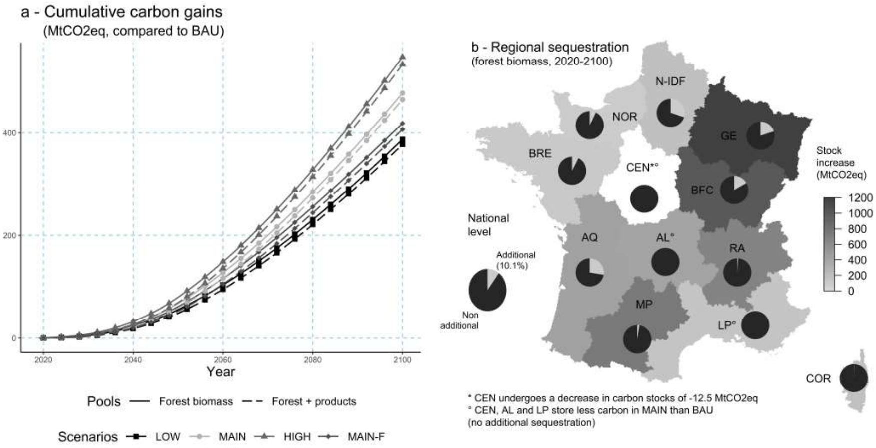


Figure 3 - Carbon dynamics at the national and regional levels: (a) cumulative carbon gains compared to BAU, (b) regional sequestration dynamics from 2020 to 2100 in MAIN.

1587x740mm (96 x 96 DPI)

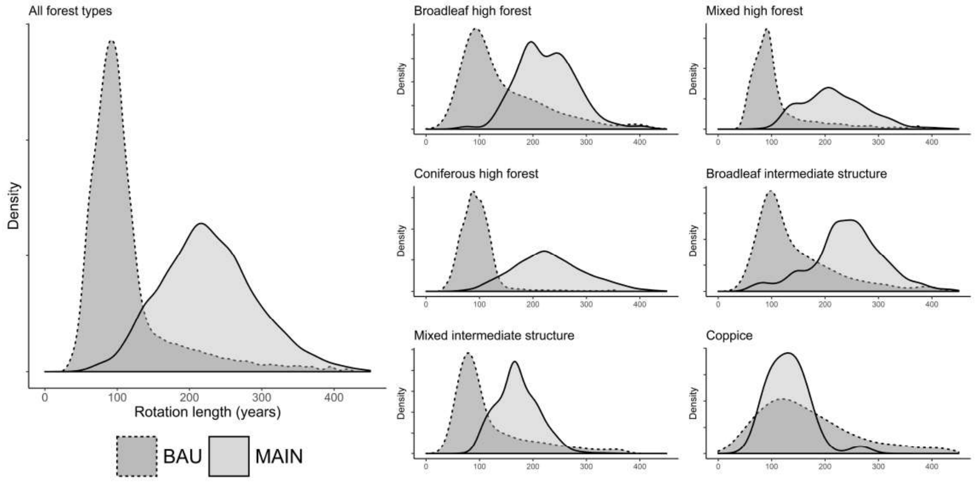


Figure 5 – Distribution of expected rotation lengths in MAIN and BAU. Values encompass all decisions taken throughout the simulations.

1587x793mm (96 x 96 DPI)

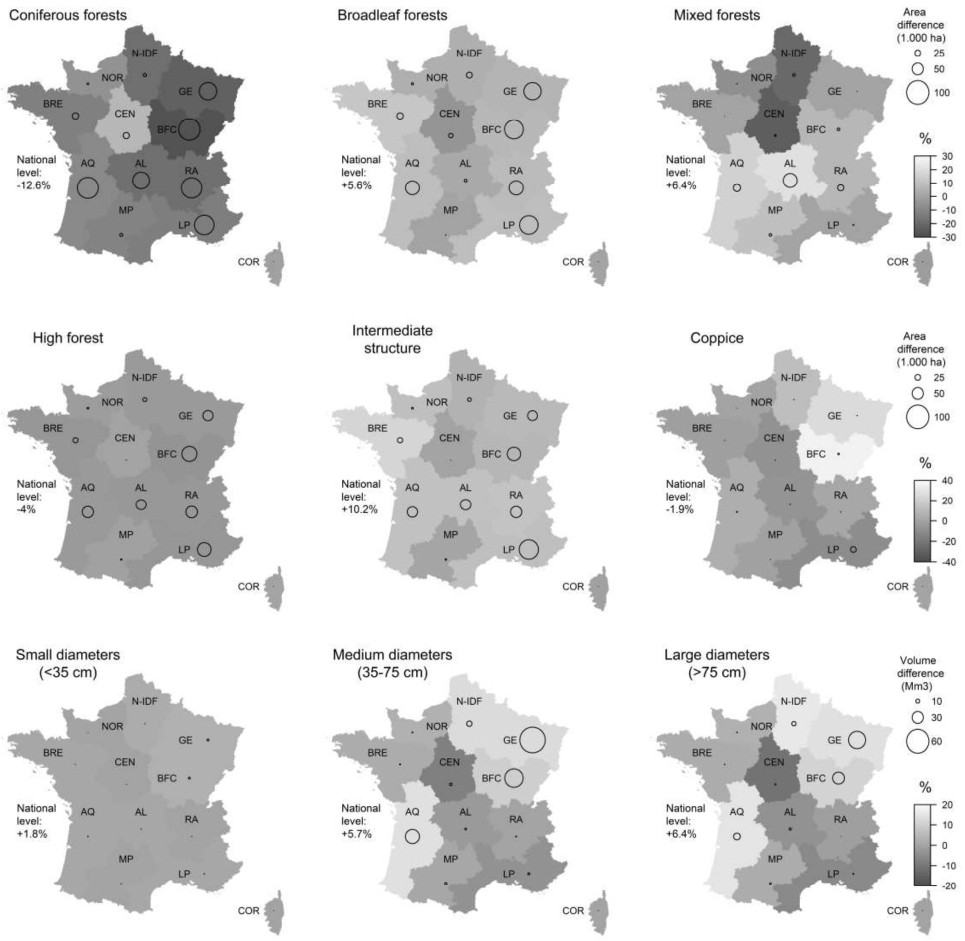


Figure 6 – Structure and composition of French forests in 2100 in MAIN compared to BAU. Circle size indicates absolute differences in areas or volumes, colours indicate relative differences.

Supplementary material n° 1: evolution of market dynamics by 10-year time periods

Table 1 – Supply (Mm^3)

	Period	BAU	MAIN-F		LOW		MAIN		HIGH	
Hardwood roundwood	*2020-2030*	5,34	5,32	(-0.21%)	5,33	(-0.17%)	5,32	(-0.21%)	5,32	(-0.27%)
	2031-2040	5,41	5,38	(-0.54%)	5,39	(-0.44%)	5,38	(-0.54%)	5,37	(-0.65%)
	2041-2050	5,49	5,44	(-0.9%)	5,45	(-0.7%)	5,44	(-0.9%)	5,43	(-1.06%)
	2051-2060	5,54	5,48	(-1.11%)	5,49	(-0.85%)	5,48	(-1.1%)	5,47	(-1.27%)
	2061-2070	5,58	5,52	(-1.11%)	5,53	(-0.84%)	5,52	(-1.09%)	5,51	(-1.27%)
	2071-2080	5,61	5,55	(-1.12%)	5,56	(-0.83%)	5,55	(-1.08%)	5,54	(-1.26%)
	2081-2090	5,63	5,57	(-1.08%)	5,59	(-0.78%)	5,57	(-1.03%)	5,56	(-1.21%)
	2091-2100	5,65	5,59	(-1.04%)	5,61	(-0.72%)	5,59	(-0.97%)	5,58	(-1.15%)
Industrial wood	*2020-2030*	38,6	38,23	(-0.95%)	38,3	(-0.78%)	38,23	(-0.95%)	38,14	(-1.2%)
	2031-2040	39,25	38,35	(-2.29%)	38,53	(-1.83%)	38,35	(-2.29%)	38,17	(-2.75%)
	2041-2050	39,91	38,32	(-3.97%)	38,67	(-3.11%)	38,33	(-3.97%)	38,05	(-4.66%)
	2051-2060	40,35	38,36	(-4.93%)	38,82	(-3.79%)	38,37	(-4.91%)	38,05	(-5.71%)
	2061-2070	40,62	38,58	(-5.01%)	39,06	(-3.83%)	38,6	(-4.97%)	38,26	(-5.79%)
	2071-2080	40,79	38,71	(-5.09%)	39,21	(-3.86%)	38,74	(-5.02%)	38,4	(-5.85%)
	2081-2090	40,87	38,77	(-5.12%)	39,3	(-3.83%)	38,82	(-5%)	38,48	(-5.84%)
	2091-2100	40,85	38,78	(-5.08%)	39,33	(-3.72%)	38,85	(-4.89%)	38,51	(-5.74%)
Softwood roundwood	*2020-2030*	20,84	20,81	(-0.12%)	20,82	(-0.1%)	20,81	(-0.12%)	20,81	(-0.15%)
	2031-2040	21,25	21,19	(-0.27%)	21,2	(-0.22%)	21,19	(-0.27%)	21,18	(-0.32%)
	2041-2050	21,64	21,54	(-0.46%)	21,56	(-0.37%)	21,54	(-0.47%)	21,53	(-0.54%)
	2051-2060	21,89	21,78	(-0.48%)	21,8	(-0.42%)	21,78	(-0.52%)	21,76	(-0.59%)
	2061-2070	22,02	21,94	(-0.33%)	21,93	(-0.41%)	21,91	(-0.48%)	21,9	(-0.53%)
	2071-2080	22,11	22,06	(-0.23%)	22	(-0.47%)	21,99	(-0.53%)	21,98	(-0.56%)
	2081-2090	22,19	22,14	(-0.2%)	22,05	(-0.63%)	22,04	(-0.67%)	22,03	(-0.7%)
	2091-2100	22,26	22,22	(-0.21%)	22,07	(-0.87%)	22,06	(-0.91%)	22,06	(-0.93%)

Table 2 – Prices (eur/m³)

	Period	BAU	MAIN-F		LOW		MAIN		HIGH	
Hardwood roundwood	*2020-2030*	112,5	114,69	(1.95%)	114,3	(1.6%)	114,69	(1.95%)	115,26	(2.46%)
	2031-2040	104,21	109,09	(4.68%)	108,11	(3.74%)	109,09	(4.68%)	110,05	(5.6%)
	2041-2050	97,3	105,18	(8.09%)	103,45	(6.32%)	105,17	(8.08%)	106,53	(9.49%)
	2051-2060	91,93	101,02	(9.9%)	98,96	(7.65%)	100,98	(9.85%)	102,42	(11.42%)
	2061-2070	88,15	97,02	(10.05%)	94,95	(7.71%)	96,92	(9.94%)	98,29	(11.5%)
	2071-2080	85,25	93,79	(10.02%)	91,67	(7.53%)	93,62	(9.82%)	94,99	(11.43%)
	2081-2090	83	91,15	(9.83%)	88,99	(7.22%)	90,89	(9.51%)	92,24	(11.14%)
	2091-2100	81,18	88,99	(9.62%)	86,77	(6.88%)	88,62	(9.16%)	89,93	(10.78%)
Industrial wood	*2020-2030*	32,68	33,78	(3.38%)	33,58	(2.77%)	33,78	(3.38%)	34,07	(4.27%)
	2031-2040	30,66	33,17	(8.18%)	32,65	(6.5%)	33,17	(8.18%)	33,68	(9.86%)
	2041-2050	29,47	33,67	(14.24%)	32,72	(11.02%)	33,67	(14.24%)	34,45	(16.88%)
	2051-2060	28,42	33,36	(17.39%)	32,19	(13.27%)	33,36	(17.38%)	34,22	(20.4%)
	2061-2070	27,69	32,49	(17.34%)	31,35	(13.19%)	32,5	(17.34%)	33,33	(20.35%)
	2071-2080	27,21	31,85	(17.02%)	30,71	(12.85%)	31,85	(17.03%)	32,68	(20.07%)
	2081-2090	26,89	31,39	(16.75%)	30,27	(12.56%)	31,39	(16.73%)	32,2	(19.77%)
	2091-2100	26,62	31	(16.46%)	29,9	(12.33%)	30,99	(16.43%)	31,8	(19.46%)
Softwood roundwood	*2020-2030*	80,15	80,67	(0.65%)	80,57	(0.53%)	80,67	(0.65%)	80,8	(0.81%)
	2031-2040	75,91	77,02	(1.46%)	76,79	(1.16%)	77,02	(1.46%)	77,24	(1.75%)
	2041-2050	73,1	74,86	(2.41%)	74,47	(1.88%)	74,87	(2.43%)	75,17	(2.84%)
	2051-2060	71,21	73,04	(2.57%)	72,69	(2.08%)	73,13	(2.7%)	73,42	(3.11%)
	2061-2070	69,97	71,5	(2.19%)	71,41	(2.06%)	71,79	(2.6%)	72,05	(2.97%)
	2071-2080	69,11	70,43	(1.92%)	70,67	(2.26%)	71,01	(2.75%)	71,24	(3.08%)
	2081-2090	68,41	69,64	(1.8%)	70,25	(2.7%)	70,56	(3.15%)	70,77	(3.46%)
	2091-2100	67,74	68,97	(1.82%)	70,04	(3.4%)	70,33	(3.82%)	70,53	(4.13%)

Table 3 – Trade (Mm^3)

	Period	BAU	MAIN-F		LOW		MAIN		HIGH	
Exports	*2020-2030*	5,28	5,07	(-4,14%)	5,11	(-3,33%)	5,07	(-4,14%)	5,02	(-5,18%)
	2031-2040	6,19	5,59	(-10,73%)	5,71	(-8,41%)	5,59	(-10,73%)	5,49	(-12,75%)
	2041-2050	7,37	6,2	(-18,87%)	6,45	(-14,26%)	6,2	(-18,87%)	6,02	(-22,43%)
	2051-2060	8,13	6,61	(-23%)	6,93	(-17,32%)	6,61	(-23%)	6,41	(-26,83%)
	2061-2070	8,42	6,85	(-22,92%)	7,19	(-17,11%)	6,87	(-22,56%)	6,64	(-26,81%)
	2071-2080	8,66	7,07	(-22,49%)	7,41	(-16,87%)	7,07	(-22,49%)	6,84	(-26,61%)
	2081-2090	8,85	7,24	(-22,24%)	7,59	(-16,6%)	7,25	(-22,07%)	7,02	(-26,07%)
	2091-2100	9	7,39	(-21,79%)	7,75	(-16,13%)	7,4	(-21,62%)	7,17	(-25,52%)
Imports	*2020-2030*	9,17	9,19	(0.19%)	9,19	(0.16%)	9,19	(0.19%)	9,2	(0.25%)
	2031-2040	9,03	9,08	(0.46%)	9,07	(0.37%)	9,08	(0.46%)	9,08	(0.55%)
	2041-2050	8,61	8,68	(0.81%)	8,66	(0.64%)	8,68	(0.81%)	8,69	(0.95%)
	2051-2060	8,42	8,5	(0.97%)	8,48	(0.75%)	8,5	(0.98%)	8,51	(1.14%)
	2061-2070	8,4	8,48	(0.95%)	8,46	(0.74%)	8,48	(0.97%)	8,5	(1.13%)
	2071-2080	8,39	8,47	(0.94%)	8,45	(0.77%)	8,47	(0.98%)	8,48	(1.14%)
	2081-2090	8,38	8,46	(0.94%)	8,44	(0.79%)	8,46	(1.01%)	8,48	(1.16%)
	2091-2100	8,37	8,45	(0.92%)	8,44	(0.8%)	8,46	(1.01%)	8,47	(1.17%)

Table 4 – Surpluses

	Period	BAU	MAIN-F		LOW		MAIN		HIGH	
Consumer surplus (Meur)	*2020-2030*	6034	6009	(-0.42%)	6013	(-0.34%)	6009	(-0.42%)	6002	(-0.53%)
	2031-2040	6118	6057	(-1%)	6069	(-0.8%)	6057	(-1%)	6045	(-1.2%)
	2041-2050	6119	6013	(-1.73%)	6036	(-1.36%)	6013	(-1.74%)	5994	(-2.04%)
	2051-2060	6139	6009	(-2.11%)	6038	(-1.63%)	6009	(-2.12%)	5988	(-2.46%)
	2061-2070	6176	6049	(-2.06%)	6075	(-1.63%)	6046	(-2.1%)	6025	(-2.44%)
	2071-2080	6202	6076	(-2.03%)	6100	(-1.65%)	6070	(-2.12%)	6050	(-2.46%)
	2081-2090	6220	6095	(-2.01%)	6115	(-1.69%)	6086	(-2.16%)	6065	(-2.49%)
	2091-2100	6232	6108	(-2%)	6124	(-1.74%)	6095	(-2.2%)	6074	(-2.53%)
Producer surplus (Meur)	*2020-2030*	1918	1945	(1.39%)	1940	(1.14%)	1945	(1.39%)	1951	(1.74%)
	2031-2040	1871	1922	(2.75%)	1912	(2.19%)	1922	(2.75%)	1932	(3.3%)
	2041-2050	1878	1953	(3.97%)	1935	(3.06%)	1953	(3.98%)	1966	(4.67%)
	2051-2060	1872	1944	(3.88%)	1928	(2.99%)	1945	(3.92%)	1958	(4.59%)
	2061-2070	1851	1917	(3.6%)	1903	(2.85%)	1920	(3.72%)	1931	(4.35%)
	2071-2080	1836	1897	(3.3%)	1886	(2.7%)	1901	(3.55%)	1913	(4.16%)
	2081-2090	1825	1882	(3.09%)	1874	(2.67%)	1889	(3.48%)	1900	(4.07%)
	2091-2100	1814	1868	(2.96%)	1865	(2.77%)	1879	(3.55%)	1889	(4.12%)

Supplementary material n° 2: evolution of management dynamics by 10-year time periods

Table 1 – Harvest volume (Mm3)

Forest type	Period	BAU	MAIN-F		LOW		MAIN		HIGH	
All	*2020-2030*	46.07	45.62	(-1%)	45.69	(-0.8%)	45.62	(-1%)	45.5	(-1.2%)
	2031-2040	46.72	45.56	(-2.5%)	45.79	(-2%)	45.56	(-2.5%)	45.34	(-3%)
	2041-2050	47.64	45.51	(-4.5%)	45.96	(-3.5%)	45.51	(-4.5%)	45.16	(-5.2%)
	2051-2060	48.02	45.32	(-5.6%)	45.9	(-4.4%)	45.3	(-5.7%)	44.89	(-6.5%)
	2061-2070	47.92	45.13	(-5.8%)	45.71	(-4.6%)	45.09	(-5.9%)	44.65	(-6.8%)
	2071-2080	47.75	44.84	(-6.1%)	45.41	(-4.9%)	44.77	(-6.2%)	44.32	(-7.2%)
	2081-2090	47.48	44.52	(-6.2%)	45.08	(-5.1%)	44.41	(-6.5%)	43.94	(-7.5%)
	2091-2100	47.15	44.19	(-6.3%)	44.7	(-5.2%)	44.03	(-6.6%)	43.55	(-7.6%)
Broadleaf high forest	*2020-2030*	12.09	11.87	(-1.8%)	11.91	(-1.5%)	11.87	(-1.8%)	11.81	(-2.3%)
	2031-2040	11.44	10.89	(-4.7%)	11	(-3.8%)	10.89	(-4.7%)	10.79	(-5.7%)
	2041-2050	11.1	10.16	(-8.5%)	10.36	(-6.7%)	10.16	(-8.5%)	10	(-10%)
	2051-2060	10.74	9.58	(-10.8%)	9.84	(-8.4%)	9.58	(-10.8%)	9.4	(-12.5%)
	2061-2070	10.33	9.16	(-11.3%)	9.42	(-8.7%)	9.16	(-11.3%)	8.97	(-13.1%)
	2071-2080	9.95	8.78	(-11.7%)	9.05	(-9%)	8.78	(-11.7%)	8.59	(-13.6%)
	2081-2090	9.59	8.46	(-11.8%)	8.71	(-9.1%)	8.45	(-11.9%)	8.26	(-13.8%)
	2091-2100	9.26	8.17	(-11.8%)	8.41	(-9.2%)	8.15	(-12%)	7.96	(-14%)
Mixed high forest	*2020-2030*	3.05	3	(-1.6%)	3.01	(-1.4%)	3	(-1.6%)	2.99	(-2.1%)
	2031-2040	2.97	2.84	(-4.2%)	2.87	(-3.4%)	2.84	(-4.2%)	2.82	(-5%)
	2041-2050	2.92	2.7	(-7.6%)	2.75	(-6.1%)	2.7	(-7.7%)	2.66	(-8.9%)
	2051-2060	2.87	2.6	(-9.6%)	2.66	(-7.6%)	2.6	(-9.6%)	2.55	(-11.1%)
	2061-2070	2.8	2.52	(-10.1%)	2.58	(-7.9%)	2.52	(-10.1%)	2.47	(-11.6%)
	2071-2080	2.74	2.45	(-10.6%)	2.51	(-8.2%)	2.45	(-10.5%)	2.41	(-12.1%)
	2081-2090	2.69	2.39	(-11%)	2.47	(-8.3%)	2.4	(-10.8%)	2.36	(-12.4%)
	2091-2100	2.66	2.36	(-11%)	2.44	(-8%)	2.38	(-10.5%)	2.33	(-12.3%)
Coniferous high forest	*2020-2030*	20.39	20.32	(-0.4%)	20.33	(-0.3%)	20.32	(-0.4%)	20.3	(-0.5%)
	2031-2040	20.36	20.2	(-0.8%)	20.23	(-0.7%)	20.2	(-0.8%)	20.17	(-1%)
	2041-2050	20.38	20.09	(-1.4%)	20.14	(-1.1%)	20.09	(-1.4%)	20.04	(-1.6%)
	2051-2060	20.25	19.93	(-1.6%)	19.97	(-1.4%)	19.91	(-1.7%)	19.86	(-1.9%)
	2061-2070	20.06	19.78	(-1.4%)	19.77	(-1.4%)	19.71	(-1.7%)	19.68	(-1.9%)
	2071-2080	19.94	19.68	(-1.3%)	19.6	(-1.7%)	19.55	(-1.9%)	19.52	(-2.1%)
	2081-2090	19.92	19.65	(-1.4%)	19.48	(-2.2%)	19.43	(-2.4%)	19.4	(-2.6%)
	2091-2100	19.97	19.67	(-1.5%)	19.42	(-2.8%)	19.37	(-3%)	19.33	(-3.2%)
Broadleaf intermediate structure	*2020-2030*	7.31	7.21	(-1.4%)	7.23	(-1.1%)	7.21	(-1.4%)	7.19	(-1.7%)
	2031-2040	8.22	7.92	(-3.6%)	7.98	(-2.9%)	7.92	(-3.6%)	7.87	(-4.3%)
	2041-2050	9.13	8.53	(-6.6%)	8.65	(-5.2%)	8.53	(-6.6%)	8.43	(-7.7%)

	2051-2060	9.79	8.96	(-8.5%)	9.15	(-6.5%)	8.97	(-8.4%)	8.84	(-9.7%)
	2061-2070	10.24	9.29	(-9.2%)	9.54	(-6.9%)	9.32	(-9%)	9.17	(-10.4%)
	2071-2080	10.56	9.5	(-10.1%)	9.79	(-7.3%)	9.55	(-9.5%)	9.38	(-11.1%)
	2081-2090	10.72	9.6	(-10.5%)	9.95	(-7.2%)	9.69	(-9.6%)	9.5	(-11.3%)
	2091-2100	10.75	9.63	(-10.5%)	10.03	(-6.8%)	9.75	(-9.3%)	9.56	(-11.1%)
Mixed intermediate structure	*2020-2030*	1.66	1.66	(-0.1%)	1.66	(-0.1%)	1.66	(-0.1%)	1.66	(-0.2%)
	2031-2040	1.8	1.8	(-0.3%)	1.8	(-0.2%)	1.8	(-0.3%)	1.8	(-0.3%)
	2041-2050	1.96	1.95	(-0.5%)	1.95	(-0.5%)	1.95	(-0.5%)	1.95	(-0.6%)
	2051-2060	2.08	2.07	(-0.6%)	2.07	(-0.5%)	2.07	(-0.6%)	2.07	(-0.6%)
	2061-2070	2.15	2.14	(-0.7%)	2.14	(-0.5%)	2.14	(-0.5%)	2.14	(-0.6%)
	2071-2080	2.19	2.17	(-0.9%)	2.18	(-0.4%)	2.18	(-0.4%)	2.18	(-0.5%)
	2081-2090	2.19	2.17	(-1.1%)	2.19	(-0.1%)	2.19	(-0.2%)	2.19	(-0.2%)
	2091-2100	2.17	2.14	(-1.3%)	2.18	(0.4%)	2.18	(0.3%)	2.17	(0.2%)
Coppice	*2020-2030*	1.56	1.55	(-0.5%)	1.55	(-0.4%)	1.55	(-0.5%)	1.55	(-0.6%)
	2031-2040	1.93	1.9	(-1.3%)	1.91	(-1.1%)	1.9	(-1.3%)	1.9	(-1.6%)
	2041-2050	2.15	2.09	(-3%)	2.1	(-2.4%)	2.08	(-3%)	2.07	(-3.4%)
	2051-2060	2.28	2.18	(-4.3%)	2.2	(-3.5%)	2.18	(-4.3%)	2.17	(-4.9%)
	2061-2070	2.35	2.24	(-4.7%)	2.26	(-3.9%)	2.24	(-4.8%)	2.22	(-5.4%)
	2071-2080	2.38	2.27	(-4.8%)	2.28	(-4.1%)	2.26	(-5%)	2.24	(-5.7%)
	2081-2090	2.38	2.26	(-5.1%)	2.27	(-4.3%)	2.25	(-5.4%)	2.23	(-6.1%)
	2091-2100	2.34	2.22	(-5.1%)	2.24	(-4.4%)	2.21	(-5.4%)	2.19	(-6.1%)

Table 2 – Share of investments in each forest type (% area, sum is equal to 100)

Forest type	Period	BAU	MAIN-F		LOW		MAIN		HIGH	
Broadleaf high forest	*2020-2030*	8.98%	8.92%	(-0.1)	8.94%	(0)	8.99%	(0)	9.08%	(0.1)
	2031-2040	9.07%	8.93%	(-0.1)	9.13%	(0.1)	9.16%	(0.1)	9.16%	(0.1)
	2041-2050	9.44%	9.17%	(-0.3)	9.13%	(-0.3)	9.1%	(-0.3)	9.08%	(-0.4)
	2051-2060	9.53%	9.14%	(-0.4)	9.04%	(-0.5)	8.97%	(-0.6)	8.94%	(-0.6)
	2061-2070	9.23%	8.9%	(-0.3)	8.89%	(-0.3)	8.82%	(-0.4)	8.79%	(-0.4)
	2071-2080	9.06%	8.68%	(-0.4)	8.73%	(-0.3)	8.66%	(-0.4)	8.62%	(-0.4)
	2081-2090	8.91%	8.44%	(-0.5)	8.57%	(-0.3)	8.51%	(-0.4)	8.48%	(-0.4)
	2091-2100	8.77%	8.31%	(-0.5)	8.42%	(-0.4)	8.35%	(-0.4)	8.32%	(-0.4)
Mixed high forest	*2020-2030*	10.78%	10.95%	(0.2)	12.55%	(1.8)	12.62%	(1.8)	12.67%	(1.9)
	2031-2040	9.67%	9.93%	(0.3)	12.1%	(2.4)	12.15%	(2.5)	12.23%	(2.6)
	2041-2050	8.74%	9.14%	(0.4)	11.76%	(3)	11.84%	(3.1)	11.88%	(3.1)
	2051-2060	8.04%	8.64%	(0.6)	11.5%	(3.5)	11.56%	(3.5)	11.59%	(3.6)
	2061-2070	7.74%	8.26%	(0.5)	11.22%	(3.5)	11.28%	(3.5)	11.32%	(3.6)
	2071-2080	7.54%	8.01%	(0.5)	10.98%	(3.4)	11.04%	(3.5)	11.08%	(3.5)
	2081-2090	7.44%	7.85%	(0.4)	10.79%	(3.4)	10.85%	(3.4)	10.9%	(3.5)
	2091-2100	7.4%	7.7%	(0.3)	10.64%	(3.2)	10.7%	(3.3)	10.74%	(3.3)

Coniferous high forest	*2020-2030*	66.48%	66.36%	(-0.1)	55.42%	(-11.1)	54.94%	(-11.5)	54.51%	(-12)
	2031-2040	67.64%	67.49%	(-0.1)	55.65%	(-12)	55.49%	(-12.2)	55.36%	(-12.3)
	2041-2050	68.17%	67.96%	(-0.2)	56.39%	(-11.8)	56.24%	(-11.9)	56.19%	(-12)
	2051-2060	68.48%	68.2%	(-0.3)	56.94%	(-11.5)	56.82%	(-11.7)	56.83%	(-11.7)
	2061-2070	68.84%	68.5%	(-0.3)	57.53%	(-11.3)	57.43%	(-11.4)	57.43%	(-11.4)
	2071-2080	68.97%	68.75%	(-0.2)	58.07%	(-10.9)	57.97%	(-11)	57.96%	(-11)
	2081-2090	68.96%	68.98%	(0)	58.49%	(-10.5)	58.38%	(-10.6)	58.37%	(-10.6)
	2091-2100	68.92%	69.07%	(0.1)	58.86%	(-10.1)	58.76%	(-10.2)	58.76%	(-10.2)
Broadleaf intermediate structure	*2020-2030*	8.17%	8.2%	(0)	17.46%	(9.3)	17.77%	(9.6)	18.01%	(9.8)
	2031-2040	8.14%	8.19%	(0)	17.57%	(9.4)	17.65%	(9.5)	17.71%	(9.6)
	2041-2050	8.25%	8.34%	(0.1)	17.32%	(9.1)	17.4%	(9.1)	17.43%	(9.2)
	2051-2060	8.42%	8.51%	(0.1)	17.14%	(8.7)	17.24%	(8.8)	17.25%	(8.8)
	2061-2070	8.47%	8.61%	(0.1)	16.94%	(8.5)	17.04%	(8.6)	17.04%	(8.6)
	2071-2080	8.48%	8.64%	(0.2)	16.74%	(8.3)	16.83%	(8.3)	16.84%	(8.4)
	2081-2090	8.53%	8.6%	(0.1)	16.55%	(8)	16.64%	(8.1)	16.65%	(8.1)
	2091-2100	8.57%	8.6%	(0)	16.34%	(7.8)	16.43%	(7.9)	16.44%	(7.9)
Mixed intermediate structure	*2020-2030*	5.06%	5.04%	(0)	5.06%	(0)	5.1%	(0)	5.13%	(0.1)
	2031-2040	4.85%	4.8%	(0)	4.98%	(0.1)	4.99%	(0.1)	5%	(0.2)
	2041-2050	4.63%	4.59%	(0)	4.86%	(0.2)	4.89%	(0.3)	4.89%	(0.3)
	2051-2060	4.64%	4.6%	(0)	4.85%	(0.2)	4.88%	(0.2)	4.87%	(0.2)
	2061-2070	4.77%	4.73%	(0)	4.88%	(0.1)	4.91%	(0.1)	4.9%	(0.1)
	2071-2080	4.93%	4.86%	(-0.1)	4.96%	(0)	4.99%	(0.1)	4.98%	(0)
	2081-2090	5.09%	5%	(-0.1)	5.08%	(0)	5.1%	(0)	5.1%	(0)
	2091-2100	5.22%	5.14%	(-0.1)	5.22%	(0)	5.25%	(0)	5.24%	(0)
Coppice	*2020-2030*	0.52%	0.53%	(0)	0.57%	(0)	0.58%	(0.1)	0.6%	(0.1)
	2031-2040	0.63%	0.65%	(0)	0.56%	(-0.1)	0.56%	(-0.1)	0.55%	(-0.1)
	2041-2050	0.77%	0.79%	(0)	0.54%	(-0.2)	0.54%	(-0.2)	0.53%	(-0.2)
	2051-2060	0.88%	0.92%	(0)	0.53%	(-0.4)	0.53%	(-0.4)	0.52%	(-0.4)
	2061-2070	0.95%	1%	(0)	0.53%	(-0.4)	0.52%	(-0.4)	0.52%	(-0.4)
	2071-2080	1.01%	1.06%	(0.1)	0.53%	(-0.5)	0.52%	(-0.5)	0.51%	(-0.5)
	2081-2090	1.07%	1.13%	(0.1)	0.52%	(-0.5)	0.51%	(-0.6)	0.51%	(-0.6)
	2091-2100	1.13%	1.19%	(0.1)	0.52%	(-0.6)	0.51%	(-0.6)	0.5%	(-0.6)

Table 3 – Expected rotation times (years)

Forest type	**Period**	**BAU**	**MAIN-F**		**LOW**		**MAIN**		**HIGH**	
All	*2020-2030*	127.45	127.24	(-0.2%)	199.25	(56.3%)	205.1	(60.9%)	215.21	(68.9%)
	2031-2040	128.31	127.89	(-0.3%)	219.97	(71.4%)	220.54	(71.9%)	214.49	(67.2%)
	2041-2050	129.59	128.88	(-0.6%)	218.19	(68.4%)	215.71	(66.5%)	221.32	(70.8%)
	2051-2060	130.5	129.53	(-0.7%)	209.62	(60.6%)	209.65	(60.7%)	211.72	(62.2%)
	2061-2070	130.79	129.56	(-0.9%)	207.41	(58.6%)	208.9	(59.7%)	209.91	(60.5%)
	2071-2080	130.92	129.63	(-1%)	208.91	(59.6%)	207.78	(58.7%)	208.41	(59.2%)
	2081-2090	131.09	129.77	(-1%)	206.67	(57.6%)	206.25	(57.3%)	208.44	(59%)

	2091-2100	131.23	129.95	(-1%)	207.54	(58.2%)	207	(57.7%)	206.22	(57.1%)
Broadleaf high forest	*2020-2030*	136.27	135.83	(-0.3%)	220.16	(61.6%)	218.72	(60.5%)	237.51	(74.3%)
	2031-2040	138.82	137.9	(-0.7%)	224.29	(61.6%)	225.57	(62.5%)	226.43	(63.1%)
	2041-2050	142.43	140.76	(-1.2%)	234.7	(64.8%)	228.42	(60.4%)	241.55	(69.6%)
	2051-2060	144.48	142.71	(-1.2%)	228.32	(58%)	228.56	(58.2%)	229.01	(58.5%)
	2061-2070	144.97	142.52	(-1.7%)	229.65	(58.4%)	228.53	(57.6%)	229.94	(58.6%)
	2071-2080	145.03	142.68	(-1.6%)	229.28	(58.1%)	229.16	(58%)	230.73	(59.1%)
	2081-2090	145.55	143.12	(-1.7%)	227.9	(56.6%)	229.58	(57.7%)	231.12	(58.8%)
	2091-2100	145.92	143.5	(-1.7%)	230.05	(57.7%)	231.47	(58.6%)	229.62	(57.4%)
Mixed high forest	*2020-2030*	108.58	108.44	(-0.1%)	193.83	(78.5%)	203.81	(87.7%)	211.66	(94.9%)
	2031-2040	109.19	108.91	(-0.3%)	217.43	(99.1%)	218.76	(100.3%)	219.51	(101%)
	2041-2050	110.81	110.18	(-0.6%)	220.91	(99.4%)	221.34	(99.8%)	221.47	(99.9%)
	2051-2060	112.03	111.07	(-0.9%)	221.37	(97.6%)	221.65	(97.9%)	221.72	(97.9%)
	2061-2070	112.29	111.32	(-0.9%)	221.13	(96.9%)	221.44	(97.2%)	221.48	(97.2%)
	2071-2080	112.48	111.51	(-0.9%)	221.03	(96.5%)	221.29	(96.7%)	221.38	(96.8%)
	2081-2090	112.84	111.68	(-1%)	221.04	(95.9%)	221.28	(96.1%)	221.54	(96.3%)
	2091-2100	113.17	111.89	(-1.1%)	221.04	(95.3%)	221.52	(95.7%)	221.6	(95.8%)
Coniferous high forest	*2020-2030*	96.36	96.33	(0%)	211.1	(119.1%)	220.85	(129.2%)	228.7	(137.4%)
	2031-2040	96.39	96.35	(0%)	232.52	(141.2%)	233.06	(141.8%)	233.46	(142.2%)
	2041-2050	96.21	96.15	(-0.1%)	234.09	(143.3%)	234.3	(143.5%)	234.25	(143.5%)
	2051-2060	96.09	96.06	(0%)	234.29	(143.8%)	234.36	(143.9%)	234.45	(144%)
	2061-2070	96.15	96.05	(-0.1%)	234.14	(143.5%)	234.2	(143.6%)	234.28	(143.7%)
	2071-2080	96.16	96.05	(-0.1%)	234.06	(143.4%)	234.16	(143.5%)	234.26	(143.6%)
	2081-2090	96.15	96.06	(-0.1%)	234.08	(143.5%)	234.17	(143.6%)	234.31	(143.7%)
	2091-2100	96.13	96.04	(-0.1%)	234.07	(143.5%)	234.2	(143.6%)	234.35	(143.8%)
Broadleaf intermediate structure	*2020-2030*	137.26	136.99	(-0.2%)	225.35	(64.2%)	233.43	(70.1%)	239.17	(74.2%)
	2031-2040	139.59	138.84	(-0.5%)	245.04	(75.5%)	245.73	(76%)	246.01	(76.2%)
	2041-2050	142.89	141.58	(-0.9%)	246.61	(72.6%)	246.8	(72.7%)	246.93	(72.8%)
	2051-2060	144.94	143.35	(-1.1%)	246.83	(70.3%)	246.96	(70.4%)	247.15	(70.5%)
	2061-2070	145.42	143.29	(-1.5%)	246.87	(69.8%)	247.16	(70%)	247.31	(70.1%)
	2071-2080	145.49	143.58	(-1.3%)	247	(69.8%)	247.21	(69.9%)	247.23	(69.9%)
	2081-2090	145.8	143.92	(-1.3%)	246.91	(69.4%)	247.23	(69.6%)	247.2	(69.6%)
	2091-2100	146.15	144.32	(-1.2%)	246.9	(68.9%)	247.16	(69.1%)	247.15	(69.1%)
Mixed intermediate structure	*2020-2030*	114	113.91	(-0.1%)	161.55	(41.7%)	167.2	(46.7%)	169.3	(48.5%)
	2031-2040	115.23	115.04	(-0.2%)	171.93	(49.2%)	172.35	(49.6%)	172.5	(49.7%)
	2041-2050	118.17	118.01	(-0.1%)	172.81	(46.2%)	173.2	(46.6%)	172.83	(46.3%)
	2051-2060	120.05	119.6	(-0.4%)	172.88	(44%)	173.02	(44.1%)	172.95	(44.1%)
	2061-2070	120.76	120.18	(-0.5%)	172	(42.4%)	172.1	(42.5%)	172	(42.4%)
	2071-2080	121.49	120.51	(-0.8%)	171.67	(41.3%)	171.88	(41.5%)	171.78	(41.4%)
	2081-2090	121.64	120.89	(-0.6%)	171.73	(41.2%)	171.88	(41.3%)	171.76	(41.2%)
	2091-2100	121.95	121.22	(-0.6%)	171.64	(40.8%)	171.83	(40.9%)	171.8	(40.9%)
Coppice	*2020-2030*	172.23	171.95	(-0.2%)	183.49	(6.5%)	186.58	(8.3%)	204.9	(19%)
	2031-2040	170.64	170.29	(-0.2%)	228.62	(34%)	227.76	(33.5%)	189.04	(10.8%)
	2041-2050	167.03	166.58	(-0.3%)	200.02	(19.7%)	190.22	(13.9%)	210.9	(26.3%)
	2051-2060	165.38	164.41	(-0.6%)	154.03	(-6.9%)	153.35	(-7.3%)	165.05	(-0.2%)

	2061-2070	165.13	163.98	(-0.7%)	140.66	(-14.8%)	149.97	(-9.2%)	154.45	(-6.5%)
	2071-2080	164.9	163.45	(-0.9%)	150.39	(-8.8%)	142.95	(-13.3%)	145.08	(-12%)
	2081-2090	164.59	162.96	(-1%)	138.35	(-15.9%)	133.38	(-19%)	144.71	(-12.1%)
	2091-2100	164.04	162.74	(-0.8%)	141.57	(-13.7%)	135.8	(-17.2%)	132.78	(-19.1%)

Table 4 – Expected revenues from timber (eur/ha)

Forest type	**Period**	**BAU**	**MAIN-F**		**LOW**		**MAIN**		**HIGH**	
All	*2020-2030*	125.62	127.02	(1.1%)	23.15	(-81.6%)	16.88	(-86.6%)	11.57	(-90.8%)
	2031-2040	108	110.52	(2.3%)	7.94	(-92.7%)	7.78	(-92.8%)	7.73	(-92.8%)
	2041-2050	88.72	92.05	(3.8%)	6.28	(-92.9%)	6.29	(-92.9%)	6.3	(-92.9%)
	2051-2060	80.41	83.71	(4.1%)	5.68	(-92.9%)	5.71	(-92.9%)	5.74	(-92.9%)
	2061-2070	78.9	81.96	(3.9%)	5.58	(-92.9%)	5.62	(-92.9%)	5.64	(-92.8%)
	2071-2080	77.82	80.6	(3.6%)	5.51	(-92.9%)	5.53	(-92.9%)	5.55	(-92.9%)
	2081-2090	76.63	79.3	(3.5%)	5.43	(-92.9%)	5.45	(-92.9%)	5.47	(-92.9%)
	2091-2100	75.76	78.35	(3.4%)	5.39	(-92.9%)	5.41	(-92.9%)	5.43	(-92.8%)
Broadleaf high forest	*2020-2030*	90.64	92.83	(2.4%)	10.16	(-88.8%)	7.75	(-91.4%)	6.37	(-93%)
	2031-2040	76.07	80.08	(5.3%)	5.22	(-93.1%)	5.11	(-93.3%)	5.05	(-93.4%)
	2041-2050	60.78	65.98	(8.6%)	3.93	(-93.5%)	3.8	(-93.7%)	3.64	(-94%)
	2051-2060	54.66	59.63	(9.1%)	3.34	(-93.9%)	3.37	(-93.8%)	3.4	(-93.8%)
	2061-2070	53.19	58.16	(9.3%)	3.28	(-93.8%)	3.31	(-93.8%)	3.34	(-93.7%)
	2071-2080	52.2	56.86	(8.9%)	3.22	(-93.8%)	3.25	(-93.8%)	3.26	(-93.8%)
	2081-2090	51.3	55.9	(9%)	3.17	(-93.8%)	3.2	(-93.8%)	3.21	(-93.7%)
	2091-2100	50.68	55.12	(8.8%)	3.12	(-93.8%)	3.14	(-93.8%)	3.17	(-93.7%)
Mixed high forest	*2020-2030*	121.56	123.41	(1.5%)	23.25	(-80.9%)	16.51	(-86.4%)	11.81	(-90.3%)
	2031-2040	105.02	108.73	(3.5%)	7.78	(-92.6%)	7.13	(-93.2%)	6.99	(-93.3%)
	2041-2050	86.84	92.1	(6.1%)	5.56	(-93.6%)	5.61	(-93.5%)	5.67	(-93.5%)
	2051-2060	78.24	84.07	(7.4%)	4.98	(-93.6%)	5.06	(-93.5%)	5.12	(-93.5%)
	2061-2070	76.13	81.63	(7.2%)	4.83	(-93.7%)	4.91	(-93.5%)	4.97	(-93.5%)
	2071-2080	74.47	79.81	(7.2%)	4.71	(-93.7%)	4.79	(-93.6%)	4.84	(-93.5%)
	2081-2090	73.14	78.45	(7.3%)	4.61	(-93.7%)	4.69	(-93.6%)	4.74	(-93.5%)
	2091-2100	72.16	77.47	(7.4%)	4.54	(-93.7%)	4.61	(-93.6%)	4.65	(-93.6%)
Coniferous high forest	*2020-2030*	152.11	153.52	(0.9%)	31.02	(-79.6%)	22.58	(-85.2%)	14.5	(-90.5%)
	2031-2040	130.72	132.94	(1.7%)	9.79	(-92.5%)	9.77	(-92.5%)	9.76	(-92.5%)
	2041-2050	108.92	111.86	(2.7%)	8.02	(-92.6%)	8.03	(-92.6%)	8.06	(-92.6%)
	2051-2060	99.66	102.35	(2.7%)	7.28	(-92.7%)	7.31	(-92.7%)	7.33	(-92.6%)
	2061-2070	98.05	100.43	(2.4%)	7.18	(-92.7%)	7.2	(-92.7%)	7.22	(-92.6%)
	2071-2080	96.92	99.04	(2.2%)	7.1	(-92.7%)	7.11	(-92.7%)	7.13	(-92.6%)
	2081-2090	95.55	97.58	(2.1%)	7	(-92.7%)	7.01	(-92.7%)	7.03	(-92.6%)
	2091-2100	94.58	96.59	(2.1%)	6.97	(-92.6%)	6.98	(-92.6%)	6.99	(-92.6%)
Broadleaf intermediate structure	*2020-2030*	87.65	89.3	(1.9%)	8.29	(-90.5%)	6.3	(-92.8%)	5.25	(-94%)
	2031-2040	74.24	77.93	(5%)	3.69	(-95%)	3.58	(-95.2%)	3.5	(-95.3%)
	2041-2050	59.54	64.48	(8.3%)	2.84	(-95.2%)	2.86	(-95.2%)	2.89	(-95.2%)

	2051-2060	53.18	58.18	(9.4%)	2.58	(-95.2%)	2.61	(-95.1%)	2.64	(-95%)
	2061-2070	51.63	56.43	(9.3%)	2.51	(-95.1%)	2.54	(-95.1%)	2.58	(-95%)
	2071-2080	50.6	55.01	(8.7%)	2.46	(-95.1%)	2.48	(-95.1%)	2.52	(-95%)
	2081-2090	49.73	54.1	(8.8%)	2.42	(-95.1%)	2.44	(-95.1%)	2.47	(-95%)
	2091-2100	49.15	53.24	(8.3%)	2.38	(-95.1%)	2.41	(-95.1%)	2.44	(-95%)
Mixed intermediate structure	*2020-2030*	87.93	88.46	(0.6%)	25.09	(-71.5%)	18.82	(-78.6%)	16.1	(-81.7%)
	2031-2040	76.1	77.21	(1.5%)	11.15	(-85.3%)	10.91	(-85.7%)	10.87	(-85.7%)
	2041-2050	61.96	63.28	(2.1%)	8.92	(-85.6%)	8.92	(-85.6%)	8.99	(-85.5%)
	2051-2060	55.63	57.11	(2.7%)	8.13	(-85.4%)	8.15	(-85.3%)	8.19	(-85.3%)
	2061-2070	54.49	55.93	(2.6%)	8.08	(-85.2%)	8.1	(-85.1%)	8.13	(-85.1%)
	2071-2080	53.56	54.97	(2.6%)	8.03	(-85%)	8.04	(-85%)	8.07	(-84.9%)
	2081-2090	52.99	54.07	(2%)	7.98	(-84.9%)	7.99	(-84.9%)	8.02	(-84.9%)
	2091-2100	52.39	53.42	(2%)	7.96	(-84.8%)	7.97	(-84.8%)	7.99	(-84.7%)
Coppice	*2020-2030*	9.05	9.44	(4.3%)	4.16	(-54%)	2.85	(-68.6%)	1.35	(-85.1%)
	2031-2040	7.09	7.71	(8.7%)	0.67	(-90.6%)	0.53	(-92.6%)	0.4	(-94.4%)
	2041-2050	5.61	6.43	(14.6%)	0.14	(-97.6%)	0.1	(-98.3%)	0.07	(-98.8%)
	2051-2060	5	5.94	(18.8%)	0.01	(-99.8%)	0.01	(-99.7%)	0.01	(-99.7%)
	2061-2070	4.86	5.82	(19.8%)	0.01	(-99.7%)	0.01	(-99.7%)	0.01	(-99.7%)
	2071-2080	4.73	5.74	(21.3%)	0.01	(-99.7%)	0.01	(-99.7%)	0.01	(-99.7%)
	2081-2090	4.68	5.7	(21.9%)	0.01	(-99.7%)	0.01	(-99.7%)	0.01	(-99.7%)
	2091-2100	4.74	5.67	(19.7%)	0.05	(-98.9%)	0.01	(-99.7%)	0.01	(-99.7%)

Table 5 – Cover change after harvest (% area harvested)

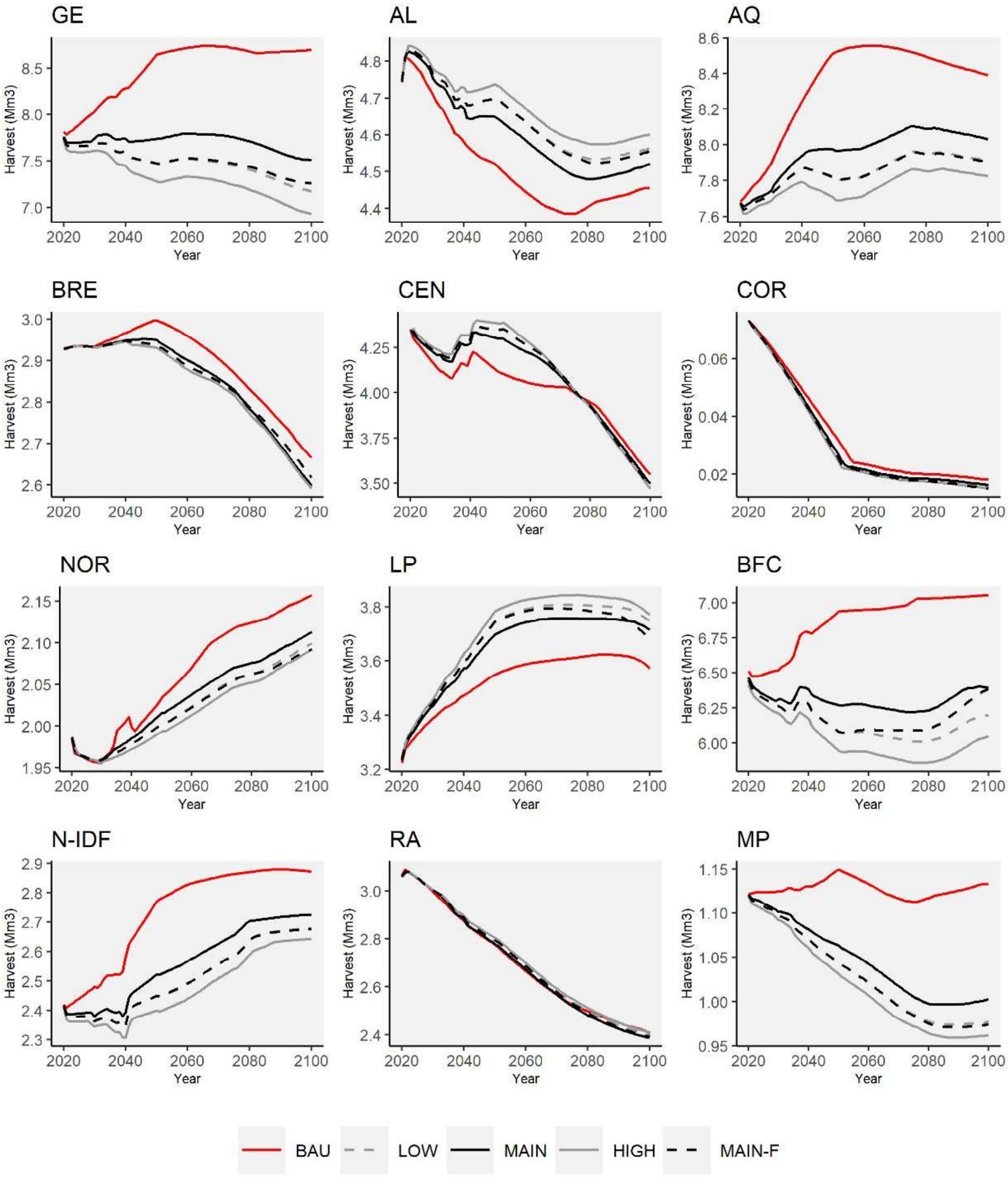
Forest type	**Period**	**BAU**	**MAIN-F**		**LOW**		**MAIN**		**HIGH**	
All	*2020-2030*	47.95%	48.01%	(0.1)	64.72%	(16.8)	65.47%	(17.5)	66.11%	(18.2)
	2031-2040	44.08%	44.08%	(0)	62.82%	(18.7)	63.09%	(19)	63.29%	(19.2)
	2041-2050	41%	40.83%	(-0.2)	60.92%	(19.9)	61.16%	(20.2)	61.28%	(20.3)
	2051-2060	39%	38.94%	(-0.1)	59.4%	(20.4)	59.61%	(20.6)	59.67%	(20.7)
	2061-2070	38.14%	37.96%	(-0.2)	58.02%	(19.9)	58.2%	(20.1)	58.24%	(20.1)
	2071-2080	37.35%	37.03%	(-0.3)	56.61%	(19.3)	56.77%	(19.4)	56.79%	(19.4)
	2081-2090	36.36%	35.85%	(-0.5)	55.06%	(18.7)	55.2%	(18.8)	55.21%	(18.8)
	2091-2100	35.2%	34.61%	(-0.6)	53.31%	(18.1)	53.44%	(18.2)	53.44%	(18.2)
Broadleaf high forest	*2020-2030*	75.38%	75.58%	(0.2)	86.45%	(11.1)	86.94%	(11.6)	87.29%	(11.9)
	2031-2040	72.07%	72.43%	(0.4)	85.63%	(13.6)	85.86%	(13.8)	86.05%	(14)
	2041-2050	68.27%	68.69%	(0.4)	84.63%	(16.4)	84.93%	(16.7)	85.12%	(16.9)
	2051-2060	66.11%	66.81%	(0.7)	83.9%	(17.8)	84.23%	(18.1)	84.43%	(18.3)
	2061-2070	65.86%	66.38%	(0.5)	83.42%	(17.6)	83.73%	(17.9)	83.91%	(18.1)
	2071-2080	65.59%	66.14%	(0.5)	83.03%	(17.4)	83.34%	(17.7)	83.51%	(17.9)
	2081-2090	65.19%	65.79%	(0.6)	82.63%	(17.4)	82.9%	(17.7)	83.06%	(17.9)
	2091-2100	64.77%	65.29%	(0.5)	82.16%	(17.4)	82.42%	(17.7)	82.57%	(17.8)
Mixed high forest	*2020-2030*	65.82%	65.46%	(-0.4)	83.93%	(18.1)	84.54%	(18.7)	85.04%	(19.2)
	2031-2040	64.13%	63.14%	(-1)	83.54%	(19.4)	83.75%	(19.6)	83.84%	(19.7)

	2041-2050	62.2%	60.66%	(-1.5)	82.21%	(20)	82.2%	(20)	82.16%	(20)
	2051-2060	60.86%	58.9%	(-2)	80.39%	(19.5)	80.32%	(19.5)	80.27%	(19.4)
	2061-2070	59.84%	57.78%	(-2.1)	78.4%	(18.6)	78.31%	(18.5)	78.24%	(18.4)
	2071-2080	58.38%	56.37%	(-2)	76.1%	(17.7)	75.99%	(17.6)	75.91%	(17.5)
	2081-2090	56.37%	54.54%	(-1.8)	73.38%	(17)	73.26%	(16.9)	73.15%	(16.8)
	2091-2100	54.12%	52.44%	(-1.7)	70.33%	(16.2)	70.2%	(16.1)	70.11%	(16)
Coniferous high forest	*2020-2030*	18.59%	18.9%	(0.3)	41.9%	(23.3)	42.95%	(24.4)	43.87%	(25.3)
	2031-2040	15.31%	15.85%	(0.5)	40.16%	(24.8)	40.51%	(25.2)	40.79%	(25.5)
	2041-2050	12.84%	13.57%	(0.7)	37.92%	(25.1)	38.34%	(25.5)	38.57%	(25.7)
	2051-2060	10.99%	12.13%	(1.1)	36.12%	(25.1)	36.57%	(25.6)	36.72%	(25.7)
	2061-2070	9.86%	11.04%	(1.2)	34.34%	(24.5)	34.78%	(24.9)	34.92%	(25.1)
	2071-2080	9.04%	10.08%	(1)	32.55%	(23.5)	32.98%	(23.9)	33.13%	(24.1)
	2081-2090	8.27%	8.95%	(0.7)	30.71%	(22.4)	31.14%	(22.9)	31.3%	(23)
	2091-2100	7.5%	8.06%	(0.6)	28.74%	(21.2)	29.18%	(21.7)	29.33%	(21.8)
Broadleaf intermediate structure	*2020-2030*	72.29%	72.29%	(0)	75.36%	(3.1)	76.01%	(3.7)	76.75%	(4.5)
	2031-2040	69.43%	69.49%	(0.1)	75.12%	(5.7)	75.56%	(6.1)	75.87%	(6.4)
	2041-2050	66.28%	66.24%	(0)	74.53%	(8.3)	74.8%	(8.5)	74.96%	(8.7)
	2051-2060	64.4%	64.36%	(0)	73.81%	(9.4)	73.97%	(9.6)	74.12%	(9.7)
	2061-2070	64.11%	63.95%	(-0.2)	73.22%	(9.1)	73.37%	(9.3)	73.48%	(9.4)
	2071-2080	63.91%	63.49%	(-0.4)	72.66%	(8.8)	72.79%	(8.9)	72.88%	(9)
	2081-2090	63.43%	62.97%	(-0.5)	71.95%	(8.5)	72.04%	(8.6)	72.12%	(8.7)
	2091-2100	62.73%	62.26%	(-0.5)	71.02%	(8.3)	71.1%	(8.4)	71.18%	(8.4)
Mixed intermediate structure	*2020-2030*	68.29%	68.23%	(-0.1)	91.48%	(23.2)	91.79%	(23.5)	92.02%	(23.7)
	2031-2040	63.58%	63.53%	(-0.1)	89.34%	(25.8)	89.6%	(26)	89.79%	(26.2)
	2041-2050	59.87%	59.46%	(-0.4)	86.96%	(27.1)	87.16%	(27.3)	87.26%	(27.4)
	2051-2060	56.38%	56.23%	(-0.2)	83.81%	(27.4)	84.07%	(27.7)	84.14%	(27.8)
	2061-2070	53.47%	53.65%	(0.2)	80.36%	(26.9)	80.62%	(27.2)	80.7%	(27.2)
	2071-2080	50.18%	50.99%	(0.8)	76.72%	(26.5)	77.01%	(26.8)	77.12%	(26.9)
	2081-2090	46.95%	48.01%	(1.1)	72.92%	(26)	73.24%	(26.3)	73.38%	(26.4)
	2091-2100	43.83%	45.11%	(1.3)	68.99%	(25.2)	69.34%	(25.5)	69.52%	(25.7)
Coppice	*2020-2030*	81.41%	81.28%	(-0.1)	99%	(17.6)	99.1%	(17.7)	99.13%	(17.7)
	2031-2040	79.82%	79.52%	(-0.3)	98.86%	(19)	98.93%	(19.1)	99%	(19.2)
	2041-2050	77.05%	76.49%	(-0.6)	98.74%	(21.7)	98.77%	(21.7)	98.78%	(21.7)
	2051-2060	74.22%	73.59%	(-0.6)	98.46%	(24.2)	98.49%	(24.3)	98.51%	(24.3)
	2061-2070	72.88%	72.09%	(-0.8)	98.16%	(25.3)	98.2%	(25.3)	98.23%	(25.4)
	2071-2080	71.44%	70.93%	(-0.5)	97.84%	(26.4)	97.91%	(26.5)	97.96%	(26.5)
	2081-2090	69.74%	69.23%	(-0.5)	97.51%	(27.8)	97.59%	(27.9)	97.66%	(27.9)
	2091-2100	67.87%	67.2%	(-0.7)	97.14%	(29.3)	97.26%	(29.4)	97.34%	(29.5)

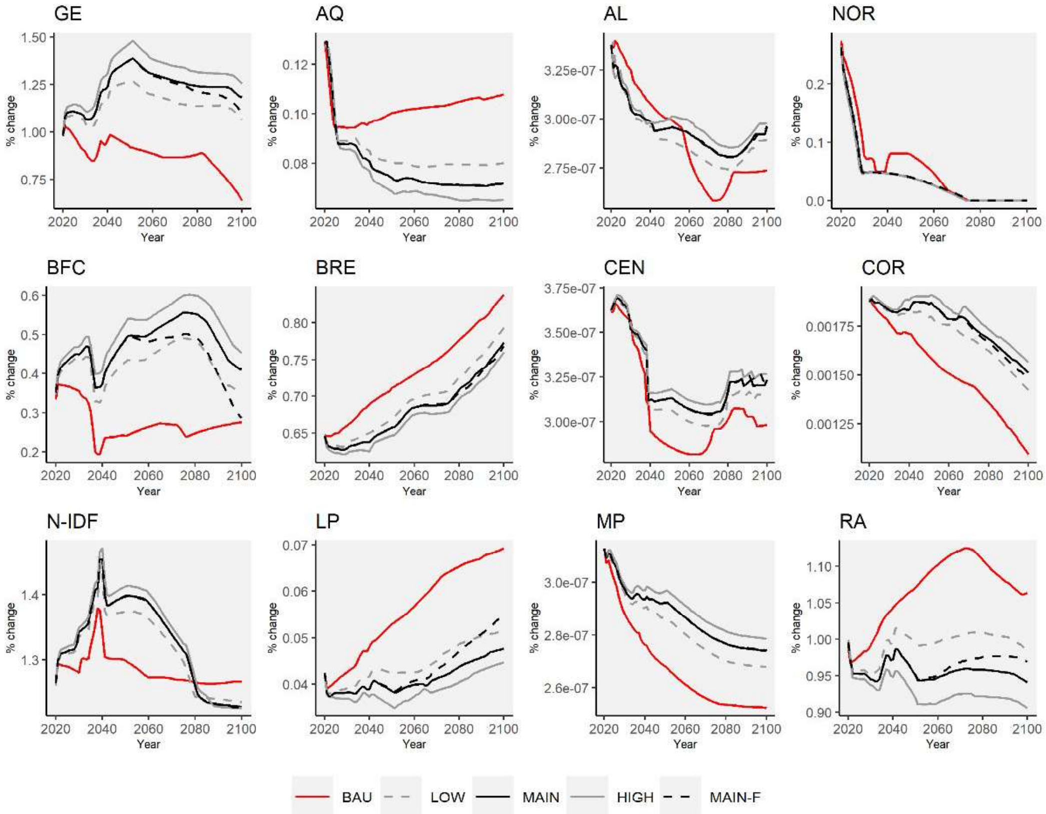
Supplementary material n° 3: evolution of regional markets.

Regions most impacted by the opportunity cost to harvesting due to carbon rents (e.g. GE, BFC, N-IDF) decrease their harvest levels. Their imports of timber products increase, and are sourced from regions where harvests increase (e.g. LP, CEN, AL). Interregional trade mostly concerns products derived from industrial wood, for which supply costs rise most.

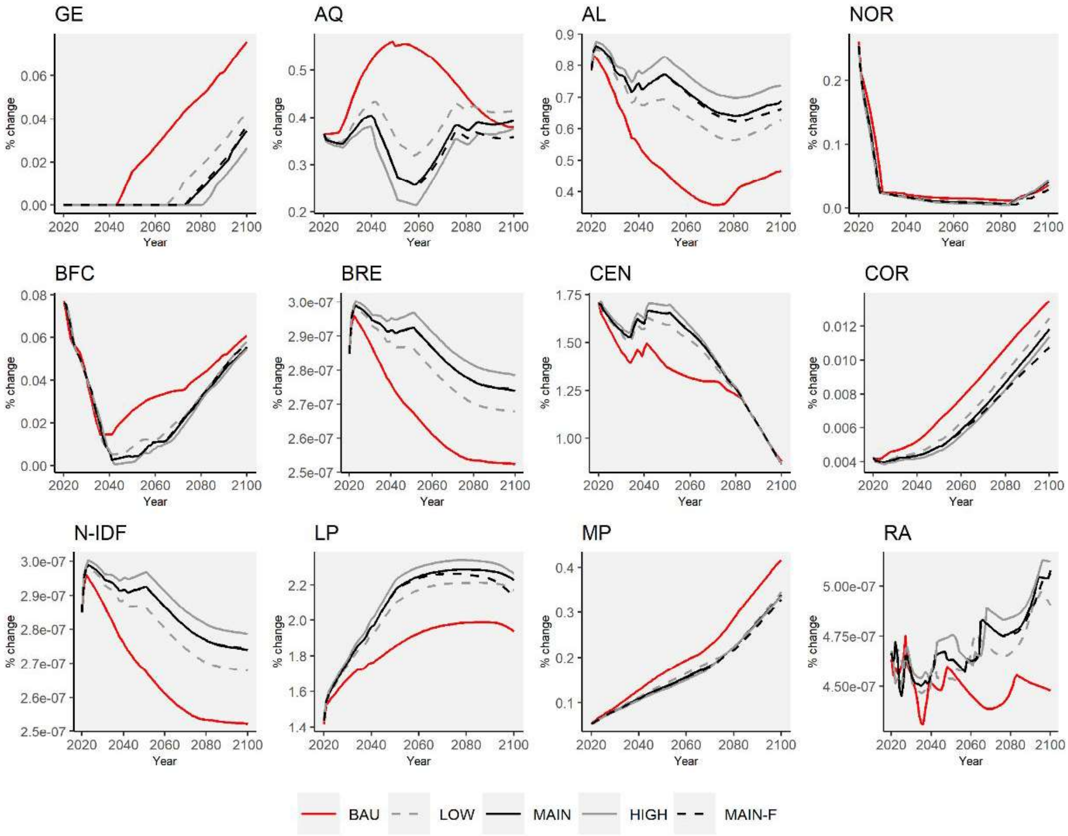
Regional harvest levels



Interregional trade within France: incoming fluxes (all products)

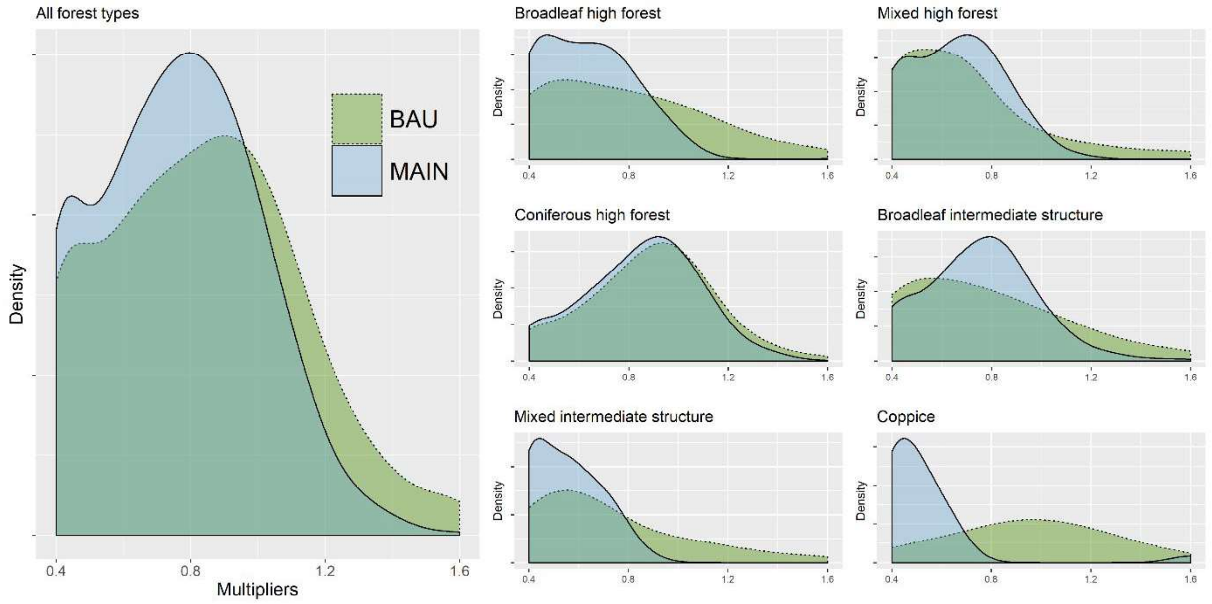


Interregional trade within France: outgoing fluxes (all products)



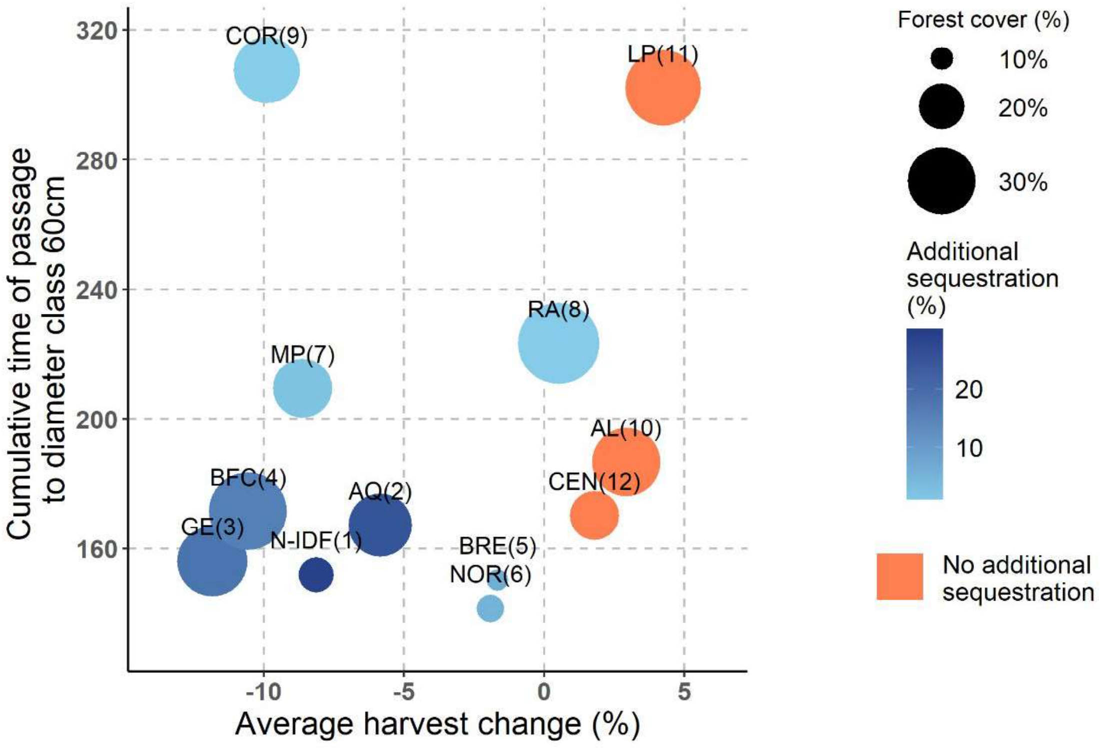
Supplementary material n° 4: distribution of growth multipliers

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.



Supplementary material n° 5: Additionality of carbon sequestration in relation to harvests, growth dynamics and forest cover.

Additional sequestration is 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 located in regions characterised by both (1) decreases in harvests and (2) fast growth dynamics, even when forest cover is low or moderate.



Supplementary material n° 6: Overview of regional investment decisions following harvests. These changes, over time, yield the landscape changes presented in the main text. Values correspond to scenario MAIN, averaged over the whole simulation. Changes are given compared to BAU.

Table 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 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)*