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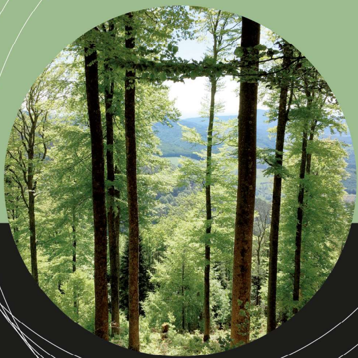
The forestry & wood sector and climate change mitigation

From carbon sequestration in forests to the development of the bioeconomy

A. Roux, A. Colin, J.-F. Dhôte and B. Schmitt, eds



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Preface

Climate change, which is already clearly evident around the world, is one of the major challenges facing humanity now and in the decades to come. Mitigating climate change requires that every business sector, production chain, household, consumer and citizen of the world must make significant changes to their production, consumption, lifestyle and use of space in order to reduce greenhouse gas emissions and anthropogenic environmental damage. Faced with these urgent objectives, public policies must define, guide, stimulate and encourage (and, if necessary, force) the societal changes needed to meet this global challenge.

Intergovernmental Panel on Climate Change (IPCC) reports clearly show that limiting the rise in the average global surface temperature to less than +2°C will require not only drastic reductions in human-induced greenhouse gas emissions, in particular by promoting a decarbonised economy, but also an increase in carbon ‘sinks’, which equate to ‘negative emissions’ (IPCC, 2018). Forests have a particular role to play in this context because of their extent, their biological functioning and the services they provide to society. On the one hand, through photosynthesis, forests can fix a proportion of atmospheric CO_2 and sequester this captured carbon in the tissues of trees and forest ecosystems. On the other hand, they provide a renewable natural resource conducive to the development of bioeconomies, which have the aim of replacing economies based on non-renewable resources and fossil fuel use, as well as reducing greenhouse gas emissions through product substitution.

While the main challenge in intertropical and boreal regions is tackling deforestation and forest resource degradation, forests and forestry in temperate regions face what may appear to be contradictory goals: to increase atmospheric carbon capture through sequestration in biomass and soils, while providing a growing share of the resources needed to produce essential material goods and energy for human societies as well as gradually renewing forests to enable them to adapt to future climate conditions. Creating a balance between these potentially competing priorities has been the subject of intense societal and scientific debate in recent years, which has prompted us to examine all aspects of these issues in greater depth.

With this in mind, INRAE and IGN, at the request of the French Ministries responsible for agriculture and forestry, have jointly undertaken a scientific assessment to shed light on the details of this debate, using the example of forests and the forestry & wood sectors in metropolitan France. The results of this important exercise are presented in this book.

The aim here is explicitly not to decide between positions, which are sometimes presented in an exaggeratedly disparate manner; rather, it is to enable stakeholders (professionals, the public, and organizations), decision-makers and citizens who feel concerned by this issue to understand the full complexity and uncertainties surrounding the trade-off between carbon sequestration in forests and the development of the bioeconomy. To this end, experts from our two organizations and some of our partners have analysed the various aspects that need to be considered when designing and implementing potential low-carbon strategies for the sustainable management of forest resources and wood-based products.

In restricting the scope of the analysis to the overall forestry & wood sector in France, the experts firstly describe the various components that must be explored in order to produce a comprehensive carbon assessment of the sector. In doing so, they highlight the areas of uncertainty in the current balance estimates, which are related to margins of error in the available data and the difficulties in setting particular coefficients and parameters essential to the establishment of these balances. On that basis, they make projections of this carbon balance up to the year 2050, a horizon that may to some appear remote, but which, on the scale of forest and climate dynamics, is very near. More specifically, these projections examine the potential impacts of three forest management strategies that differ mainly in their levels of resource extraction (and renewal) in order to supply the bioeconomy.

This forward-looking, predictive analysis firstly highlights that, regardless of the chosen option, the carbon balance of the entire forestry & wood sector in France is likely to continue improving. This confirms the major role of this sector in climate change mitigation. However, in addition to the uncertainties already identified for the establishment of the current carbon balance, further uncertainties concern the evolution of particular coefficients and technical parameters that influence the results of the projections. For example, will the growth rate of French forests be maintained as stands age? How might changes occur in the amount of greenhouse gas emissions avoided by using forest products instead of those which today produce more greenhouse gases? While these uncertainties make it difficult to identify a single management strategy with the most favourable outcome in terms of carbon balance, they can, as will be seen in the following pages, guide discussion on wood uses that should be encouraged to improve the carbon balance through strategies to support the development of the bioeconomy.

In addition to analysing the carbon balance, the group of experts chose to add two further dimensions, both of which are original and essential, to better clarify the future role of the sector in mitigating climate change. Firstly, the use of an economic model encompassing the entire French sector allows the identification of economic obstacles that must be removed in order to deploy strategies aimed at increasing harvests. Consequently, as Verkerk *et al.* (2020) correctly noted, the response of the forestry & wood sector and the management strategies to which they will be subject will be very sensitive to future climatic conditions, as well as to the major biotic and abiotic disturbances that forests will probably experience more frequently over coming decades. Although very difficult to conceptualize and model, especially given their nature and frequency of occurrence, the simultaneous analysis of these two additional dimensions has been attempted here. It provides an initial assessment of the sector's resilience and carbon balance in the face of such changes and events.

Daniel Bursaux, director general of IGN
Philippe Mauguin, president-director general of INRAE

Forward

This publication is the result of a study carried out by INRA (now INRAE, National Research Institute for Agriculture, Food and the Environment) and IGN (National Institute for Geographic and Forestry Information), at the request of the Ministry of Agriculture and Food and the High Council for Food, Agriculture and Rural Areas. It was conducted by INRAE's Directorate for Collective Scientific Expertise, Foresight and Advanced Studies (DEPE). As with all work conducted by DEPE, this study was carried out according to the principles and rules for conducting expert assessments and studies laid down by this institution (INRAE-DEPE, 2018). DEPE carries out three types of projects, mostly commissioned by public authorities or external partners.

– Collective Scientific Assessments (ESCo) involve the compilation of existing scientific knowledge to highlight achievements, uncertainties and knowledge gaps, and to reveal the latest scientific debates.
– When the available literature is unable to precisely answer the questions posed by the public authorities, a multidisciplinary study-type approach is used. These studies are similar to the ESCo, and indeed integrate the ESCo approach, but complement it with the creation of new data (collection, statistical analysis, calculation and simulation).
– Prospective studies offer visions of the future (or scenarios) for discussion by exploring, as systematically as possible, hypothetical scenarios based on available scientific knowledge.

The study presented here includes elements specific to each of these three approaches. It examines how carbon balances can be established for the forestry and wood sector - taken here in its broadest sense, i.e. the entire forestry sector system and the activities related to the management, harvesting and value-adding of wood-based products - and their associated uncertainties. Firstly, it adopts an expert assessment approach using a review of the international scientific literature to define and discuss the assumptions and parameters to be adopted for each component along production chains that are likely to sequester or release carbon dioxide (CO_2). The detailed results of this first stage were the subject of a first report directed to the ministry responsible for agriculture (Dhôte *et al.*, 2015). This study also considers alternative forest management strategies up to 2050 using a prospective approach, which develops scenarios and seeks to quantify their long-term consequences. Finally, the study quantifies the effects of the scenarios considered using existing simulation tools, which therefore exposes their limitations. The detailed results of the complete study are available in the full report and its numerous annexes (see Roux *et al.*, 2017).

This project was coordinated by the project leader Alice Roux (INRAE-DEPE), and assisted by Marc-Antoine Caillaud and Kim Girard (INRAE-DEPE) who provided logistical and administrative support. The scientific steering was initially entrusted to Jean-François Dhôte (INRAE), with Antoine Colin (IGN) and Bertrand Schmitt, then Director of the DEPE (INRAE), taking over as planned and ensuring the finalization of the study and the coordination of this publication. To carry out this work, a group of experts, comprising researchers and technical experts from a variety of institutional and scientific backgrounds, was formed to cover the various themes addressed in the study. This group was composed of: Alain Bailly (FCBA[1]); Claire Bastick (IGN); Jean-Charles Bastien (INRAE); Alain Berthelot (FCBA); Nathalie Bréda (INRAE); Sylvain Caurla (INRAE); Jean-Michel Carnus (INRAE); Antoine Colin (IGN); Barry Gardiner (INRAE); Hervé Jactel (INRAE); Jean-Michel Leban (INRAE); Antonello Lobianco (AgroParisTech); Denis Loustau (INRAE); Benoît Marçais (INRAE); Céline Meredieu (INRAE); Luc Pâques (INRAE); Éric Rigolot (INRAE); Laurent Saint-André (INRAE). A summary of the expertise and contributions of each of the experts can be found at the end of the book.

The supervision of the study was entrusted to a steering committee which brought together a group of administrative, technical and professional experts around the relevant units of the ministry responsible for agriculture, which commissioned the study. This process ensured constructive exchanges of different perspectives within the French forestry & wood sector. In addition to representatives of the Ministry of Agriculture, participants included: Pierrick Daniel, Lise Wlérick, Frédéric Branger and Florian Claeys (DGEP); Pierre Claquin and Élise Delgoulet (CEP); Sylvie Alexandre (MTES-MCT); Bernard Roman-Amat, then Michel Vallance (CGAAER); Jean-Luc Peyron (GIP Ecofor); Isabelle Feix and Miriam Buitrago (Ademe); Pierre Brender, Joseph Lunet and Elisabeth Pagnac-Farbiaz (MTES-DGEC); Gérard Deroubaix and Estelle Vial (FCBA); Christine Deleuze (ONF); Olivier Picard (CNPF-IDF); Jacques Chevalier (CSTB); Yves

Duclerc (MTES-DHUP); Julia Grimault (I4CE).

A first draft of this book greatly benefited from the constructive criticism of Erwin Dreyer (INRAE), Jean-Marc Guehl (INRAE), Mériem Fournier (AgroParisTech) and Jean-Luc Peyron (GIP Ecofor), whose comments were invaluable. Jean-Marc Guehl was also directly involved in the drafting process, helping us to place the approach used within the context of global forest issues in the face of climate change.

Although the following is the sole responsibility of the authors of this publication, the contributions of the members of the steering committee and the scientific reviewers were important, both in the development of the study strategy and in the interpretations of the results. We would like to thank them all for their contributions.

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1 FCBA, l'Institut technologique Forêt cellulose bois-construction ameublement (The Technological Institute for Forest Cellulose, Timber and Wood Furniture).

The role of the forestry & wood sectors in mitigating climate change

Forest ecosystems are at the heart of major global and climate change issues, in particular due to their major role in the carbon cycle. The scope of this book is limited to the French metropolitan forests and forestry sector. However, in order to fully grasp its scope, it is useful to recall some basic elements concerning forests as a whole, and in particular their sensitivity and importance in the face of current environmental disturbances and imbalances characterizing the 'Anthropocene', which Crutzen and Stoermer (2000) define as an 'epoch characterized by the major impact of human activities on the biosphere and the earth system as a whole'. It is also useful to consider the diversity of contexts across major regions of the globe with respect to changes in carbon budgets and the consequences for atmospheric CO_2 levels.

A global issue

The world's forests cover 4 billion hectares, or 31% of the Earth's land area. They contain 60-75 per cent of the carbon of the terrestrial plant biomass and 40-53 per cent of the carbon of the terrestrial biosphere, i.e. the total organic carbon contained in vegetation and soils. This represents nearly 860 gigatonnes of carbon (GtC), or nearly 3,150 $GtCO_2$, a level equivalent to that of CO_2 currently present in the atmosphere.

Forests make a major contribution to the global natural carbon cycle through highly significant exchanges with the atmosphere. The gross primary production of forests, i.e. the photosynthetic input of CO_2 into ecosystems, is estimated at 220 $GtCO_2$/year, i.e. nearly 50% of that of all terrestrial plant cover (Gough, 2011). At the ecosystem scale, this incoming flow is largely offset by a reverse flow of CO_2 related to the energy expenditure of plant metabolism and growth, but also of microorganisms associated with plants or involved in the transformation and decomposition of dead organic matter in litter and soil. Wood extraction and natural disturbances (such as storms, biotic stresses, climatic extremes or fires) also contribute to this outgoing flow through the resulting plant mortality or from combustion. However, the positive difference between CO_2 inflows and outflows on a global scale means that forest ecosystems are a net carbon sink.

These dual characteristics (their high carbon content and their significant bidirectional exchanges with the atmosphere) imply the existence of strong functional relationships between changes in the carbon stock in forest ecosystems and atmospheric CO_2 concentration. Understanding and modelling these relationships requires their consideration in the context of imbalances in the carbon cycle caused by disturbances linked to human activities. In this respect, two main types of factors (*extensive* and *intensive*) should be considered:

– land use changes, most often transforming areas with high carbon concentrations in biomass and soils (forests, savannahs, grasslands, wetlands, etc.) into crops or plantations, and sometimes into degraded land, have led to a transfer of carbon from terrestrial ecosystems to the atmosphere, resulting in a slow increase in atmospheric CO_2 since the 1850s (Le Quéré *et al.*, 2018). This is a source of endogenous CO_2, whereby no additional carbon is added to the natural carbon cycle. These practices currently account for 14% of global CO_2 emissions (Figure 1.1), with tropical forest clearance and degradation predominant;

– CO_2 emissions related to the use of fossilised carbon are an exogenous source of carbon. This source currently accounts for 86% of total emissions, at an average of 40.2 $GtCO_2$/year over the last decade (Figure 1.1). They are the predominant source of atmospheric CO_2 increases (410 parts per million in 2019, an increase of 50 per cent over the pre-industrial level of 275 parts per million), which have grown exponentially since the 1950s. Various lines of evidence suggest that the terrestrial biosphere has responded to anthropogenic CO_2 emissions over the past century by increasing gross primary production in proportion to the increase in atmospheric CO_2, primarily through the direct stimulation of photosynthesis (Cernusak *et al.*, 2019). Consistent with this finding, simulation models that quantify carbon fluxes and balances at the continental ecosystem scale indicate that the terrestrial biosphere currently sequesters 11.5 $GtCO_2$eq/yr through carbon accumulation in biomass and soils. This represents 29% of total annual CO_2 emissions, thus contributing, along with the oceans (23%), to mitigating the accumulation of CO_2 in the atmosphere (Figure 1.1). In the coming decades, the adverse impacts of global climate change (droughts, heatwaves and interactions with biotic stresses) on terrestrial productivity and carbon storage may outweigh the direct positive effects of increased CO_2 on photosynthetic activity.

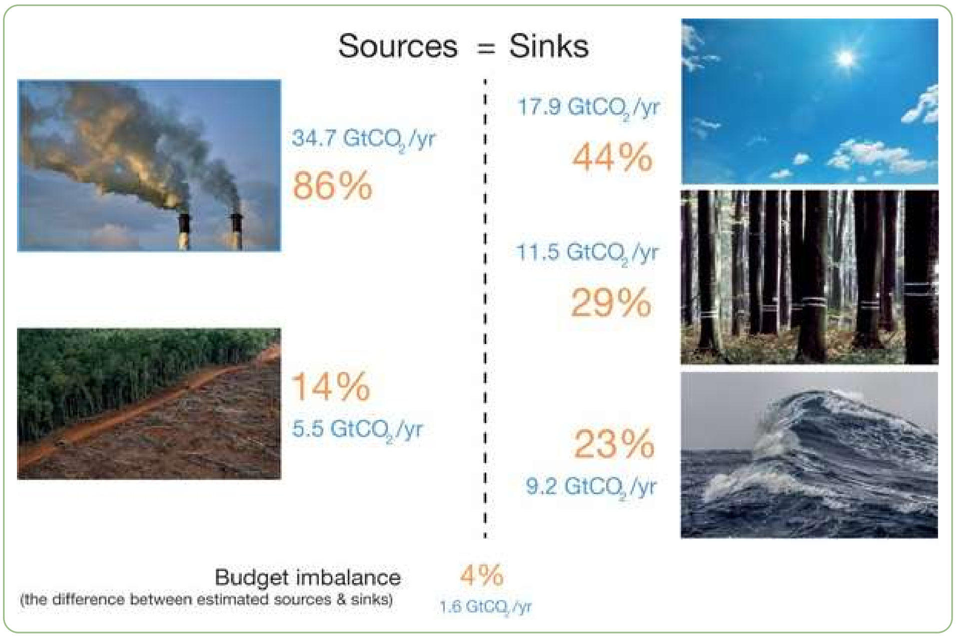

Figure 1.1. Global emissions (sources) of CO_2 related to human activities (fossil fuel use and land-use change including deforestation) for the period 2009-2018. Source: Global Carbon Project (Friedlingstein *et al.*, 2019).

44% of total emissions remain in the atmosphere, while 29% of emissions are sequestered in terrestrial ecosystems (mainly forest ecosystems).

The current terrestrial CO_2 sink, resulting from the combined effects of these two major factors, is heavily concentrated in forests (Pan *et al.*, 2011). The FAO's Global Forest Resources Assessments (FRAs) provide estimates of changes in carbon areas and stocks at the scale of major forest regions (MacDicken, 2015), which show highly contrasting dynamics. Overall, forests have suffered a net decrease of nearly 130 million hectares over the last 25 years (-3%). The rate of net deforestation was decreasing until 2015, but the phenomenon remains significant, especially for tropical primary forests, which have been reduced by 222 million hectares (-11%) over the same period. The current terrestrial CO_2 sink is *ultimately* the result of carbon storage by undisturbed or minimally disturbed, temperate or boreal forests (which are increasing in area), but also tropical forests, whose contribution outweighs the carbon emissions from deforestation and forest degradation (Pan *et al.*, 2011).

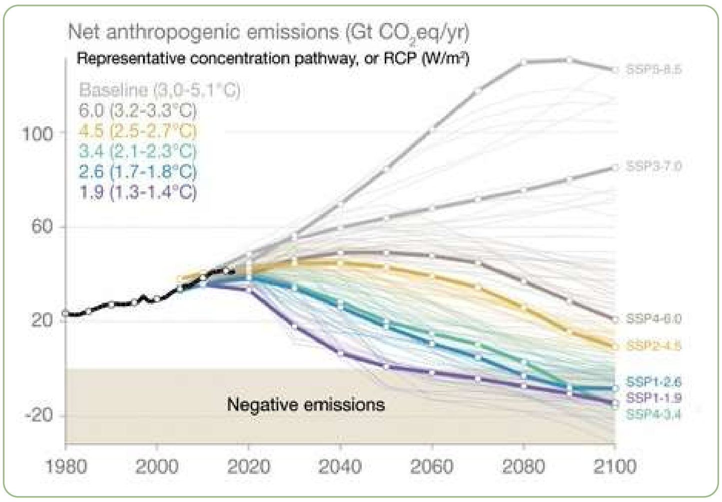

Figure 1.2. Projected gross CO_2 emissions from human activities (fossil fuel use and land-use change) to 2100 based on Shared Socioeconomic Pathways (SSPs), Representative Concentration Pathways (RCPs) and Integrated Assessment Models (IAMs). Source: Global Carbon Project (Riahi *et al.*, 2017; Rogelj *et al.*, 2018).

The thin lines correspond to the results of a set of simulation models for each of the SSP × PCR scenarios (colour coded) with the thick line representing the median. The black line represents observed historical values. The global temperature changes associated with each level of radiative forcing (RCP) correspond to levels of warming for 2100 relative to the pre-industrial baseline (1850-1900). Scenarios limiting warming to +2°C or less (SSP1-2.6, SSP1-1.9 and SSP4-3.4) would require negative net emissions for the second half of the 21st century.

Forest planning and management practices can be used to enhance carbon storage in forests. Stand aging is one option under consideration. Recent assessments have focused on the potential for additional carbon storage through the nature-based solutions[2] of reforestation or afforestation using local species. Despite their limitations (land-use conflicts, social acceptability, etc.), these approaches can contribute to the objective of limiting global warming to 1.5°C to 2°C, according to the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2019). This goal would require net CO_2 emissions to become negative during the 21st century (Figure 1.2). Forest plantations can contribute to these goals and, in an environment of expanding plantations (4% of total forest area in 1990 rising to 7% in 2015) as noted by the FAO (Payn *et al.*, 2015), China and India's extremely ambitious programmes are worth noting. In addition to the benefits in terms of carbon storage, this strategy also seeks to increase the availability of wood resources for downstream user sectors, which can reduce pressure on natural or semi-natural forest resources.

Global wood harvests are estimated at 3.3 billion cubic metres per year – corresponding to about 3.3 $GtCO_2eq$/year – equally divided between wood for energy and wood for lumber and pulp (Houghton and Nassikas, 2017). This value is significant when compared to that of storage in ecosystems (11.5 $GtCO_2eq$/year of net carbon sequestration in forests); it should be noted, however, that this estimate refers to systems managed according to sustainable forest management principles aimed at ensuring that resources are renewable. It is also important to consider the positive externalities related to the use of low carbon footprint products from renewable forest resources, rather than from other materials or energy sources that consume more fossil carbon in their manufacture and use. The use of wood-based products avoids the release of fossil carbon into the atmosphere, and the impact of this substitution effect is very significant in the net balance of CO_2 emissions (Geng *et al.*, 2017).

The French forestry & wood sector and its challenges

Greenhouse gas emissions reduction and carbon storage are major global objectives that must be addressed at national levels in order to limit ongoing climate change. With their capacity to store carbon, and therefore to mitigate the increase in atmospheric CO_2, forests and, more broadly, the forestry & wood sector, represent strategic areas for the mitigation of climate change. This is due to the combination of dynamic and reversible carbon storage in both ecosystems and the products derived from the sector, and the cumulative and permanent substitution resulting from the use of wood as a substitute for competing, non-renewable energies or materials with less favourable carbon balances (Eriksson *et al.*, 2012).

The forests of mainland France cover 16.7 million hectares, of which 15.9 million hectares are available for wood production, i.e. 30% of the total land area (IGN, 2016). It is estimated to have doubled in extent since the historical minimum around 1830 (Bontemps, 2017). This expansion has steadily continued since 1975 at an average rate of 66,000 ha/year (Denardou *et al.*, 2018). In parallel, the volume of standing timber has doubled in fifty years, making the French forest resource the third largest in Europe after Germany and Sweden, which it should soon surpass on current trends. This stock is increasing by 27 million cubic metres of wood per year (Hervé *et al.*, 2016). The French forest is heterogeneous across all scales, from the landscape level (afforestation rates among forest ecoregions range from less than 10% to almost 70%) to the parcel level; coppice forests on eastern limestone plateaus, for example, contain high species richness, whereas the vast Mediterranean coppice forests are usually composed of a single species. Three-quarters of the forests are privately owned, with the state holding 9% of the surface area (State-owned forests) and local collectivities holding 17% (mainly communal forests). With approximately 3.3 million individual owners, 36% of the private forest is composed of areas smaller than 10 ha, while 47% are larger than 25 ha (FCBA, 2016). The IGN lists more than 100 woody species in French forests. The 12 most abundant species represent just 40% of the total standing volume. Hardwoods include common, sessile and pubescent oaks, beech, chestnut, hornbeam, and ash, while softwoods include silver fir, Norway spruce, Scots and maritime pine, and Douglas fir. Hardwood trees account for 67% of the surface area, 64% of the standing volume and 60% of its annual increase (IGN, 2016). Silvicultural methods vary considerably, due to the multitude of owners, and the wide variety of environmental opportunities and management constraints. Primary processing industries (pulp and paper, fibreboard or particleboard, plywood, sawn timber) are concentrated in a wide band from south-west to north-east (Aquitaine, Auvergne-Rhône-Alpes, Centre-Val de Loire, Burgundy-Franche-Comté, Grand-Est). The hardwood processing industry has been in continuous decline for thirty years, with softwood currently accounting for 80% of sawn lumber production. Regardless of the type of wood (hardwoods or softwoods), large and very large logs are more difficult to sell, due to the mechanised harvesting methods and current industrial processes and technologies that are more suited to intermediate-sized logs (reconstituted wood, canter sawing, etc.). The use of wood energy is rapidly increasing, often to the detriment of industrial wood (or even lumber), due to supply limitations.

The French forest-wood sector, which has remained largely artisanal for a certain number of species, is now at an important juncture due to the climate crisis. Firstly, awareness of the risks associated with global warming should in theory encourage stakeholders across all sectors to favour a proactive approach based on anticipation, transformation, planning, and diversification of their activities, which requires long-term investment. Secondly, the emergence of the bioeconomy[3] is pushing the forestry & wood sector to become a key source of supply for this new economy, thus increasing the scale and ambition of its production goals (Sedjo and Sohngen, 2013; Mathijs *et al.*, 2015). Finally, foresters have long been implementing various multi-purpose forest management practices that ensure a balance between wood production and other ecosystem services (mostly non-market-based) provided by forests (biodiversity protection, quality water, management, climate regulation etc.). This has become more formalised following the major international conventions resulting from the Rio Summit, as well as European nature protection and biodiversity directives. The specific forms of this multi-purpose practice are now being questioned, both by changes to the issues involved such as the structuring role of hazards in recent forestry dynamics, and by changes to certain constraints (remote environmental impacts resulting from international trade, the re-emergence of land-use pressures resulting from the relocation of production, and enhanced sustainability objectives).

Forestry mitigation levers

Among the many public policies that directly and indirectly affect the forestry & wood sector, those related to climate are gradually gaining in importance. The debate in Europe in recent years has focused on different strategies to enhance the already considerable role of forests in mitigating climate change (Nabuurs *et al.*, 2015).

Currently, the majority of forests in Europe are sequestering carbon, with removal levels well below net biological growth. This is most pronounced in France (approximately 70 MtCO_2/year), due to the size of the forested area and the range of species and pedoclimatic conditions that are more or less favourable to forest growth and harvesting.

With regard to climate change, this accumulation is mixed. On the one hand, it creates a very significant carbon sink that offsets France's gross emissions by 10% on average (Citepa, 2017). On the other hand, poor management over large areas and the increasing levels of standing timber may lead to increased vulnerability to the impacts of climate change in the medium and long term, particularly with regard to major disturbances (droughts, storms, fires, and pest outbreaks), which could result in massive releases of carbon into the atmosphere and threaten accrued carbon benefits (Seidl *et al.*, 2014; Galik and Jackson, 2009). At the same time, the option of curbing further accumulation through increased harvesting within a sustainable resource management framework can also lead to climate benefits via fossil carbon emission reductions from the use of wood instead of competing resources, whether as a material or as an energy source, and whether directly or at the end of its life cycle.

Decision-makers must therefore decide how to manage forests in order to best mitigate climate change via four possible CO_2 emission limitation tools (Pingoud *et al.*, 2010; Thürig and Kaufmann, 2010; Beauregard *et al.*, 2019; Valade *et al.*, 2018):

- carbon storage within the ecosystem;
- carbon storage in wood-based products;
- the reduction of CO_2 emissions from human activities by substituting wood-based products for products made from materials that produce higher emissions;
- the reduction of CO_2 emissions from energy sources by substituting fossil fuels with wood as an energy source.

In simple terms, the interplay between these four (non-independent) tools results from two major trade-offs, which are relatively easy to manage via public policies. The first concerns the use of forested land (resuming management, or even intensification, versus continued extensification). The second concerns the respective importance of the different industrial forest carbon uses (solid wood, fibre, chemicals, energy, etc.), along with the competition and synergies between these uses, basic technologies and competing materials (Schwarzbauer and Stern, 2010).

Managing these trade-offs must involve consideration of the different services required from the forests. In particular, some conservation schemes lead, for reasons unrelated to climate but justified by other desired effects such as biodiversity conservation, to the accumulation of carbon. Trade-offs must be considered at appropriate spatial and temporal scales. In a sustainable forest management context, the issues occur at the level of massifs and production basins rather than at the level of individual stands. Over time, immediate effects on carbon storage or industrial activity must be balanced against delayed effects arising from the more or less pronounced impacts of future disturbances in an environment of increased risk. As a managed and productive natural environment, it is inappropriate to consider it in terms of a soil-forest-atmosphere continuum in isolation while ignoring the indirect consequences of wood use (by substitution). Forest management is an integrated activity which, in addition to balancing functions, can provide an in-depth response to the different aspects of the climate challenge, i.e. simultaneously integrating climate change mitigation while protecting against its consequences through the adaptation of practices, increasing the overall resilience of the system to major disturbances and ensuring stability of the range of ecosystem services provided by forests. Finally, the forest management response to these issues must be considered at a location-specific context, i.e., by biogeographic region, type of tenure and type of stand, thus responding to specific sets of issues, opportunities and constraints that may require locally tailored solutions.

An innovative assessment of the mitigation potential of the French sector

This assessment of the potential contribution of forests and the forestry & wood sector to national climate policy, with its opportunities and constraints, should provide the necessary insights for the design of new public policy instruments. To explore this issue, we have pursued two non-independent objectives:

– from a practical perspective, propose a method for assessing the carbon balance of forests and the forestry & wood sector that factors in the major components simultaneously in order to address the needs identified by Guehl *et al.* (2016): "Clearly, the current international accounting rules for carbon sequestration or CO_2 emissions avoided are insufficient and do not provide a basis for an effective policy to mitigate climate change. It is time to acknowledge this and propose from these, or in parallel, a global method for assessing the carbon balance of forests and timber".

– from a scientific perspective, jointly implement three dynamic models to take into account the main interactions: climate-vegetation, economic behaviour of stakeholders, spatially distributed dynamics of tree populations by size, and sensitivity of the forest ecosystem to major abiotic and biotic disturbances.

Of the four main tools to mitigate CO_2 emissions by the forestry & wood sector, identified with a view to improving the carbon balance of the sector (Madignier *et al.*, 2014; Roux *et al.*, 2017), two directly relate to carbon storage. The first refers to the forest ecosystem itself (standing wood, dead wood and forest soils), while the second concerns wood or wood-based products after they have been removed from the forest and used within the forestry & wood sector. Two other, less direct tools relate to the greenhouse gas emissions avoided through the use of wood products rather than competing products that emit more greenhouse gases. These wood-energy and wood-material substitution effects (Lippke, 2009) differ considerably in nature. The former may not necessarily favour the use of wood, as it is inefficient compared to sources such as gas, while wood combustion is responsible for carbon emissions. The latter, unrelated to the carbon content of wood, mainly reflects the fact that wood processing may emit less greenhouse gases than competing materials, particularly because it requires less energy. The use of wood in a hierarchical, or cascading fashion, i.e. by favouring material uses before industrial uses, and then energy uses at the end of the cycle, allows the optimisation of the overall substitution effect of wood products.

How are these four levers currently being used in French forests and the forestry and timber sector? How could their role be increased in the future? The hypotheses and coefficients used to calculate the carbon balance of the sector in France were first refined and discussed on the basis of a detailed analysis of the international scientific literature. Three contrasting forest management scenarios, regarded as plausible by

2050, were then developed:

– the ‘Extensification’ scenario can be considered as accentuating the current trend toward decreasing resource use;

– the ‘Territorial dynamics’ scenario is marked by strong regional differences which will prolong the current discrepancies between those that continue to actively manage and those that remain persistently less interventionist, thus significantly increasing the volumes withdrawn annually due to the expansion of the French forest resource;

– the ‘Intensification’ scenario involves more active forest management. This would lead to significant increases in harvesting rates (particularly in private forests) and a 500,000 ha reforestation plan over ten years will increase productivity in targeted areas in the medium term (Hedenus and Azar, 2009). This last scenario thus reflects and elaborates on the main elements proposed by CGAAER (Madignier *et al.*, 2014).

The consequences of these three contrasting scenarios on resource dynamics, harvesting levels and the use of harvested wood were simulated up to 2050 by combining the results of multiple models. At the heart of the system is the IGN’s MARGOT resource model[4]. It provides, over five-year periods, changes in standing stock, annual volumes of dead wood, and volumes harvested for different uses, as defined externally to the model, unless the scenario predicts a continuation of the current trend. On the basis of these results, we have calculated, over five-year time periods from 2016 to 2050, the carbon balance of the various segments of the French forestry & wood sector: carbon storage in the forest ecosystem (standing, dead wood and soil); and greenhouse gas emissions avoided by substitution effects in the energy and materials sectors.

Simultaneously with and independently of the simulations with the MARGOT model, the ‘Extensification’ and ‘Intensification’ scenarios were subject to economic analyses conducted using the FFSM[5] economic model. By examining the economic feasibility of these scenarios and the changes that the sector would need to undergo for them to occur, particularly in terms of processing and consumption of wood products, FFSM permitted the identification of the expected gains within the sector when implementing either of these scenarios.

To take into account the possible intensification of climate change, we supplemented the MARGOT demographic model with results from the GO+ model, which more directly integrates the biophysical processes involved in forest growth.

In addition to the trending effects of climate change, some major disturbances may, prior to 2050, affect French forests and their carbon storage capacities to a greater or lesser degree. Therefore, three types of major disturbances have been examined for certain management scenarios:

– a major wildfire episode, aggravated by climate change;

– a devastating large-scale storm, such as the Lothar and Martin storms of 1999 or Klaus storm of 2009 that devastated large areas of French forest, in the knowledge that such an extreme event is often followed by an outbreak of bark beetles on conifers, and subsequent fire episodes in the context of increased drought;

– several types of biological invasions affecting pines or oaks.

The impact of these major environmental shocks on the carbon balance was estimated for each segment of the forestry & wood sector, while incorporating cascading effects.

With a 2050 time horizon, which is more distant than that examined by most previous studies, this study analyses different forest management strategies in order to determine how best to use forest management strategies to mitigate climate change. Although this is too short a time frame to represent some of the long-term phenomena driven by forest dynamics, it still allows for an integrated comparison of various options for resource management. To this end, the three differing scenarios for the sector’s development were created, and a coherent reforestation plan was designed, based on the specific characteristics of French forests, in order to significantly increase the supply of wood products and materials beyond 2050. The effects of these scenarios on the dynamics of the forestry & wood sector were simulated using all three models (MARGOT, FFSM and GO+) simultaneously – within their methodological limits – as these models have rarely been run interactively and with such a long time horizon. The establishment of carbon budgets for the different segments of the forestry & wood sector is also based on assumptions and coefficients which are subject to numerous uncertainties identified in the published scientific literature, particularly with regard to certain key factors in the processes. Finally, given the climatic, biotic and abiotic threats that could affect French forests in the coming decades, it was necessary to include in the analysis not only the potential impacts of climate change, but also those of major disturbances. The latter are very difficult to model, but are integrated as a series of associated risks in a novel and realistic form, but which increases the complexity of the system.

By simultaneously addressing a range of issues, this study sits at the limit of current knowledge, as well as the capacity of currently-available analytical tools. The results here should therefore be taken, as always, with due caution. In particular, the significant uncertainties relating to some key processes, and the precise decisions that must be made in order to conduct such work, should be taken into consideration. While these choices are rational and considered, they are sometimes constrained by the available tools or by the variety of possible options. Nevertheless, they were made with as much rigour as possible

The methodology of this study reflects the complexity of decision-making in uncertain situations, i.e. in dynamic, unsteady conditions, and based on incomplete knowledge. This is common to other fields of activity requiring long-term forecasting, but is particularly important for forests, given the inertia of the relevant processes and the increasing frequency and severity of forest damage. A system of relevant models and a set of parameters, even if uncertain, provide a useful basis for informing discussions on how to guide forest management in order to mitigate climate change.

This book presents the principal results of the study, the methodological details and full results of which can be found in Roux *et al*. (2017) and its annexes. For ease of use, this book is divided into three parts, which are structured as follows:

– Firstly, based on a review of the literature, a detailed analysis was made of the assumptions and coefficients relating to the carbon balance of each segment of the forestry & wood sector, as well as the major uncertainties inherent within each of these segments (Chapter 1). This step permitted the calculation of the current carbon balance of the different segments of the French forestry & wood sector, thus leading to an understanding of the contribution of each of the climate change mitigation levers (Chapter 2). On this basis, the carbon balance of the forest & wood sector is likely to change by 2050 on the basis of specific factors as well as changes in the coefficients and assumptions mentioned above;
– The logic behind the development of the three forest management change scenarios up to the year 2050 is presented in the second part. The three scenarios are explained and analysed in detail (Chapter 3). In order to quantify their effects up to 2050 in terms of the carbon balance and in economic terms, they were implemented using a simulation approach, the results of which are presented in Chapters 4 and 5;
– Part 3 forms a sensitivity analysis in relation to the three reference scenarios for forest management changes up to 2050. The effects of intensifying climate change (Chapter 6) and/or major disturbances (Chapter 7) on the carbon balance of the forestry & wood sector are described and estimated. For this purpose, contrasting climate change scenarios were defined, as well as the use of knowledge of past major biotic and abiotic disturbances that could threaten forests into the future (e.g. in 2050). The effects of these climate scenarios and major disturbances require further simulation in order to measure their impact on the carbon balance of the forestry & wood sector up to 2050.

Finally, the main interest and novelty of this study lies in its integrative nature. It associates, at the French metropolitan level, the upstream forestry sector, including the role of forest management and development, and the downstream industrial sectors that utilize these forest resources. The various climate change mitigation instruments can be considered together with their interactions and trade-offs. As will be seen throughout this book, many questions remain unresolved in a context where the use of ecosystem products by humans solely to satisfy their needs remains at the centre of many debates (Haberl *et al.*, 2007; Erb *et al.*, 2016).

Forest policies are unique in that they require trade-offs in a structural context of uncertainties associated with the long growth period of trees and the complexity of the multiple interactions between biological, natural and social processes such as climate, the economy, natural risks, and the perceptions and expectations of rural and urban populations, etc., which also evolve over the medium and long term. Despite the extent of the uncertainties linked to the acceleration of the rate of climate change, it is more necessary than ever to shed light on the probable future of the forest-wood system by identifying the obstacles and opportunities in various scenarios. In this context, two scientific studies (Roux *et al.*, 2017; Valade *et al.*, 2018) and an approach strongly focused on environmental concerns (du Bus de Warnaffe and Angerand, 2020) which was recently published in France, propose alternative scenarios for forest management and timber harvesting. For its part, the research presented in this book aims to contribute to the analyses of the role of the forestry & wood sector in mitigating the greenhouse effect, by describing in the most transparent manner possible, given the scientific knowledge and tools currently available, the anticipated and documented impacts of different forest development options on the carbon balance.

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2 Nature-based solutions are defined by the IUCN as "actions to protect, sustainably manage and restore natural or modified ecosystems to directly address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits".

3 The bioeconomy can be viewed as a vast undertaking to reconfigure processes and production methods in order to move towards a decarbonized economy. It includes circularity, renewable resource use, the limits set by the sustainability of upstream practices and downstream recycling, low emissions and pollution, but also the consumption of scarce mineral resources (Bihouix, 2014).

4 MARGOT. *MAtrix model of forest Resource Growth and dynamics On the Territory scale*.

5 FFSM. *French Forest Sector Model* (modèle du secteur forestier français).

Part I

The current carbon balance of the forestry & wood sector

In France, as throughout the world, forests and the forestry & wood sector are now considered a strategic area of activity for climate change mitigation (Grassi *et al.*, 2017; Madignier *et al.*, 2014). They combine both a carbon storage effect in forest ecosystems and wood products, and a substitution effect of wood for fossil materials and other energy sources that emit more greenhouse gases. Before projecting various scenarios of forest management changes to a distant horizon, it is necessary to specify the accounting methods used to determine the effects of each of these four levers on the mitigation of net greenhouse gas emissions. An analysis of current scientific knowledge enables us, on the one hand, to specify or update the coefficients and assumptions used to calculate the carbon balance of the forestry & wood sector at the current state and, on the other hand, to examine the limits and uncertainties relating to each of the storage and substitution components. On this basis, an estimate of the current carbon balance of the French forestry & wood sector is proposed, and a preliminary analysis is made of how this is likely to evolve in the long term. This will depend on particular key factors such as changes to forest management or climate, both of which may impact forest dynamics and the use of wood products in the sector through to 2050, as well as the value of particular coefficients and assumptions used in the calculations.

Beyond the debates on the options to improve the carbon balance of the sector, the question arises as to whether it is more beneficial in the long term to promote *in situ* carbon storage in the forest ecosystem by limiting harvests or, conversely, to promote *ex situ* carbon storage in wood products and increase substitution effects by encouraging the use of products from the forestry & wood sector.

Chapter 1
Mitigation capacity of the different segments of the forestry & wood sector

The review of the international scientific literature conducted for this study aimed to identify the assumptions and coefficients relating to storage and substitution for the four previously identified mechanisms (sequestration in the forest ecosystem, sequestration in wood products, material substitution and energy substitution[6]), in order to calculate the carbon balance of the French forestry & wood sector. This literature review is used to define the value of the coefficients and the assumptions that can be applied to the French setting and to specify the limits and uncertainties that may affect them.

Assessment of carbon storage in the forest ecosystem

Carbon storage in the forest ecosystem results from its absorption of CO_2 from the atmosphere through photosynthesis, and applies to living biomass (both above and below ground), dead wood and forest soils.

Carbon storage in living forest biomass

In France, the national reporting of greenhouse gas emissions and recovery to the United Nations Framework Convention on Climate Change (UNFCCC) is carried out by the Technical Reference Center for Air Pollution and Climate Change (CITEPA). It summarises the CO_2 flows into (biological production) and out of (wood removals) the above-ground and root biomass of trees during each reporting period.

In specific terms, these values are initially calculated by the National Forest Inventory (IFN) in terms of the volume of 'strong stem wood' (i.e. the volume of the main trunks of trees, excluding branches, to a diameter of 7 cm at the top of the tree). They are then converted into carbon mass within the stem, branches and roots using a series of equations and coefficients specially adapted to the characteristics of French forests in terms of tree species and shape, in relation to silvicultural practices and growing conditions. The total aerial volume (including stem, branches and twigs) is estimated using volume calculations (allometric equations), which consider the different forest species present in France (Dupouey *et al.*, 2010). Root volume is calculated in proportion to total aerial volume, using an expansion factor corresponding to an average for forest species found in France. These total tree volumes are then converted into quantities of dry matter using average wood infradensity coefficients from a meta-analysis conducted by Dupouey *et al.* (2010). These results are finally converted into carbon mass. From these calculations, the average conversion coefficients for the 'IFN volume' to 'carbon mass' can be derived. Although contingent on the definitions of the various factors and characteristics of French forest resources at the time of the inventory, these mean values are very useful for rapidly estimating carbon stocks from the standard volumetric data used in forestry. These mean values were compared with the homologous values identified in the literature for other forested countries.

Table 1.1 summarizes the variation in factors identified in this study.

Table 1.1. Range of variation in transformation coefficients of IFN strong stem wood volumes to total aerial volume of C and CO_2, France (current state in bold).

	Softwood			**Hardwood**		
Ranges of Values	**Low**	**Midpoint**	**High**	**Low**	**Midpoint**	**High**
Carbon concentration	0.45	**0.475**	0.50	0.45	**0.475**	0.50
Infradensity (t/m^3)	0.36	0.40	**0.44**	0.52	**0.55**	0.58
BEF[1] (roots)	1.20	**1.30**	1.30	1.20	**1.28**	1.30
BEF[1] (branches)-Colin (2014)	1.25	**1.30**	1.35	1.50	**1.56**	1.60
BEF[1] (branches) CARBOFOR		1.34			**1.61**	
Integrated coefficients (t/m^3) for:						
C/m^3 VBFstem[2] IFN	0.24	0.32	0.39	0.42	0.52	0.60
CO_2/m^3 VBFstem[2] IFN	0.89	**1.18**	1.42	1.55	**1.91**	2.21
C/m^3 TAV[3]	0.19	0.25	0.29	0.28	0.33	0.38
CO_2/m^3 TAV[3]	0.71	**0.91**	1.05	1.03	**1.23**	1.38

[1] BEF (*biomass expansion factor*): coefficient used to estimate the total aerial volume (stems, branches and crown) from the strong stem volume, in order to more fully assess the carbon sequestered in the forest.
[2] VBFstem (volume of the stem up to the cut-off, known as 'strong stem wood'): volume of wood contained in the main stem, i.e. from ground level up to a cut-off of 7 cm in diameter at the top of the tree.
[3] TAV: total aerial volume (stem + branches + twigs).

This results in integrated coefficients that allow the conversion of the IFN strong stem wood volume into the mass of carbon or CO_2. The midpoint values for softwood and hardwood are, respectively, 1.18 and 1.91 tCO_2/m^3 of strong stem wood volume in France (line 8). The variation around these midpoint values is ± 20-25% for softwoods and ± 15-20% for hardwoods. The coefficients for the branches alone are estimated at 1.30 for softwoods and 1.56 for hardwoods with a variation of ± 4% (line 4).

Although the branch expansion factors used to estimate the total aerial volume from the stem volume are high (which has, since 2004, led to persistent concerns about possible overestimation, particularly for hardwoods), the volume estimation method has been tested favourably on the different types of coppice/high forest mixed stands (Dupouey *et al.* 2010), and for beech, as part of the ANR Emerge project (Colin, 2014). These coefficients are also consistent with the comprehensive analysis reported in Longuetaud *et al.* (2013). French research over the past ten years has therefore boosted confidence in the estimation of the aerial volume of forest trees, particularly deciduous trees, and removed a well-known obstacle to the efficient use of this resource.

The current biomass calculation method is based on average wood infradensity values by species from an international meta-analysis. To reduce uncertainty and improve the reliability of carbon stock estimates, the XyloDensMap applied research project has been measuring the wood density of all trees inventoried by the IGN since 2016 (regardless of pedoclimatic conditions, species, age, and forest management practices). This INRAE-led project will provide, in a relatively short time frame, biomass data that are fully consistent with and as precise as volume data, i.e., offering a high degree of national and regional representativeness, and their variations.

Carbon storage in dead wood

For several years, IGN has been carrying out a dead wood survey (separating standing and ground dead wood) as part of its standard measurement protocol in each plot. This information can be used in a forecasting model if both dead wood inputs (annual mortality, harvest residuals due to logging) and outputs (dead wood decomposition) can be simultaneously estimated. The literature review was therefore focused on providing information on the annual decomposition rate of dead wood.

The different categories of dead wood have been identified and their initial stocks assessed (Table 1.2). In the IGN measurements, only dead wood decomposing in the forest was estimated. Windfalls showing no trace of life are included in the estimate of dead wood on the ground, while other windfalls remain in the living trees category.

Table 1.2. Initial stocks of dead wood included in the calculation of the sector's carbon balance over the 2010-2015 period, in $MtCO_2eq$ (source IGN).

Dead wood categories	Stock of dead wood ($MtCO_2eq$)		
	On the ground	Standing	Total
< 7 cm	63.3		63.3
Large hardwoods	103.5	78.4	181.9
Large softwoods	63.7	34.5	98.2
Total	230.5	112.9	343.4

To assess the dead wood category, we assumed that inputs comprised the total aerial volume of trees at the time of mortality (with branches falling from live trees and stump inputs considered as direct inputs to the ground stock), and that the rate of carbon release from dead wood followed an exponential trend, with a loss parameter expressed as a half-life. In this case, the half-lives were set at 30 years for large hardwood dead wood, 10 years for large softwood dead wood, and 5 years for small pieces of dead wood (branches < 7 cm in diameter). In other words, on average throughout the forests of mainland France, half of the carbon stored in a piece of dead wood left in the forest is still present after 30, 10 or 5 years, depending on the category of dead wood under consideration. The choice of a long half-life reduces the annual output coefficient (here, the rate of degradation) and increases the average stock. Annual storage in the dead wood compartment is therefore strongly dependent on the half-life; the values we have chosen are consistent with the results of the meta-analysis by Zell *et al.* (2009).

Carbon storage in forest soils

The establishment of the international initiative known as '4 per 1,000; Soils for Food Security and Climate', which aims to increase carbon storage in all the world's soils every year (Paustian *et al.*, 2016), shows that the issue of carbon storage in soils is now crucial. However, most assessments of carbon storage by forests do not consider forest soils due to the lack of robustness of the available data. Where possible, we have tried to integrate them into the estimation of the carbon balance of the sector. We based our analysis on the latest international knowledge, and factored in the distribution of carbon in forest soils in relation to their structure, soil carbon dynamics (driven in particular by microorganisms), and the impact of global changes and management practices. At the same time, we have considered data on average carbon storage values in forest soils obtained from the French Renecofor network (the French component of the European ICP Forest, Level II monitoring network[7]), which shows an increase in soil carbon content between the two surveys spaced fifteen years apart.

Initial carbon stock in forest soils to a depth of 1 m, according to the latest available data, was estimated at 344 tCO_2eq/ha, for a total stock of 5 520 $MtCO_2$eq. On this basis, the French forest soils could be considered to function as carbon sinks, in connection with the former agricultural, pastoral or forest uses of which they still show evidence (Dupouey *et al.*, 2002). The rate of sequestration observed over the last 15 years within the RENECOFOR network is 0.19 tC/ha/yr under hardwoods and 0.49 tC/ha/yr under softwoods, representing 0.73 tCO_2eq/ha/yr under hardwoods and 1.80 tCO_2eq/ha/yr under softwoods (Jonard *et al.*, 2017).

By extrapolating the values from the RENECOFOR network to all French production forests, according to their distribution by species group (hardwood, softwood, mixed), an estimate of 15 $MtCO_2$eq/year of storage in forest soils for the whole of metropolitan France is obtained.

It should be stressed that the RENECOFOR network was not designed to be a representative sample of French forests as a whole. It is a collection of 102 selected stands in public forests (state or communal), with average silvicultural characteristics (within the range of what can be found throughout forests) for 11 principal species. They differ in principle from the 'average French forest' in several respects (ownership, history of land use and silvicultural management, specific composition, etc.). Consequently, the national average value is estimated to be 7.25 $MtCO_2$eq/year, slightly less than half of the value extrapolated from the RENECOFOR observations. This rate is assumed to decrease to 6 $MtCO_2$eq/year beyond 2030, limited by exponential convergence, the impact of warming and management on process rates, and the impacts of past (increased forest area) and current (species change) use.

These two values for soil storage, taken here as approximations, only roughly represent the average sequestration across France, and cannot be used for regional applications. For an estimate of carbon storage in soils up to 2050, and thus to differentiate between the management strategies envisaged up to 2050, it would be necessary to more thoroughly model soil dynamics by explicitly including interactions with climate and changes in management practices. Further research is therefore necessary:

– for a better understanding of the processes driving carbon storage in forest soils;
– to estimate the additional storage capacity of forest soils according to soil type, age of the forest, context (climatic zone, atmospheric pollution) and silvicultural practices (combination of data sets from the Soil Quality Measurement Network[8] and mapping of new and old forests in France);
– and, lastly, to develop a model for the future change in soil carbon stocks that can be applied at the national scale.

The different assumptions and coefficients used to estimate carbon storage in the French forest ecosystem are summarized in Table 1.3.

Table 1.3. Coefficients and assumptions for estimating current carbon storage in forest ecosystems.

	Variables and coefficients		Sources
Forest biomass	Variables: Gross organic production, harvest, harvest residuals, mortality	–	IGN

Dead wood	Annual decomposition rate (hardwood)	2.3% (30 years)[1]	Zell *et al.* (2009)
	Annual decomposition rate (softwood)	6.9% (10 years)[1]	
	Annual decomposition rate (harvest residuals)	13.9% (5 years)[1]	
	Initial stock	Hardwood 181.9 $MtCO_2eq$	IGN
		Softwood 98.1 $MtCO_2eq$	
		Waste (< 7 cm) 63.3 $MtCO_2eq$	
Soils	Annual sequestration (hardwood)	7.25 $MtCO_2eq$/year until 2030, then 6 $MtCO_2eq$/year	Roux *et al.* (2017), annex 3 Review of international literature and RENECOFOR network
	Annual sequestration (softwood)		
	Initial stock	5,520 $MtCO_2$	RENECOFOR network

[1] Associated half-lives

Assessment of carbon storage in wood or wood-based products

The use of wood, and the lifespan of the long-lasting products produced from it, are the key variables influencing carbon storage in wood products. The international literature focusing on the estimation of carbon stocks in wood products enabled us to assess the half-life of carbon stocks in these products, and the trends in the development of carbon stocks in the sector. This was done in terms of absolute and relative contributions, with possible differentiation between sub-sectors deemed relevant (see Roux *et al.*, 2017, Annex 4).

In order to estimate the annual carbon sequestration in wood products, two independent dynamic systems were studied (one for pulpwood, and the other for lumber), assuming no trade outside metropolitan France. These systems are supplied each year by the products derived from forests, and are depleted according to an exponential rule such that the half-life of the products is 20 years for LW or 5 years for PW. The two systems were also assumed to be in equilibrium at the beginning of the evaluation period, i.e. product inputs are considered to compensate very accurately for outputs, and annual storage is zero in the first year of the analysis period.

Table 1.4. Coefficients and assumptions used in the estimation of current carbon storage in wood products.

Variables and coefficients		**Sources**
Availability/harvest of lumber, pulpwood and energy wood		Volumes from IGN's MARGOT modelling tool (for 2015-2050)
Breakdown by use between lumber, pulpwood and energy wood		Breakdown by usage from the FFSM modelling tool data
Annual lumber decomposition rate	3.4% (20 years)[1]	Madignier *et al.*, 2014

		Expert opinion
Initial 2016 stock of lumber	300 $MtCO_2eq$	IGN
Annual decomposition rate of pulpwood	13.9% (5 years)[1]	Madignier *et al.*, 2014 Expert opinion
Initial 2016 stock of pulpwood	80 $MtCO_2eq$	IGN

[1] Associated half-lives

The combination of assumptions shown in Table 1.4 results in current stock estimates (2016) of 300 $MtCO_2eq$ and 80 $MtCO_2eq$ for lumber and pulpwood, respectively. By comparison, the CARBOSTOCK study conducted by the FCBA using 2005 data estimated the stock of wood products at 313 $MtCO_2eq$ (FCBA, 2008).

Estimation of the greenhouse gas emissions avoided through substitution effects

Substitution effects result from the use of wood as a substitute for competing energies or materials that potentially emit more greenhouse gases and therefore have less favourable carbon balances. In order to assess them, it is therefore necessary to assess the greenhouse gas emissions resulting from the transformation of wood into each of the various and differing products, and to compare the results of these assessments with the greenhouse gas emissions from the use of the alternatives (e.g. concrete beams versus wooden beams). By design, although central to understanding the role of forests and their products in climate change mitigation, these substitution effects are not credited to forests in the reporting approach used for the United Nations Framework Convention on Climate Change’s sector-specific emissions balances.

Assessing these substitution effects is particularly challenging to achieve and thus to manipulate. The first difficulty stems from the great variety of wood products in question and the products that can be replaced by each wood product. Any summary approach, such as the one we use throughout this study, tends to reduce, in most cases to its simplest form, the number of wood products and alternatives considered, and uses identical substitution coefficients for any product belonging to each of the few broad product categories (e.g. energy wood, pulpwood and lumber), thus missing the refinement of product-by-product evaluations. In addition, these assessments for both wood products and their alternatives are based on life cycle assessment approaches, which seek to determine the environmental impacts of any product or use by tracking them from their source to the end of the life of the product or service provided. The estimation of substitution effects based on these approaches therefore implies, for each wood product, a comparison between its production chain and other complete production chains, with a strictly identical framework. Substitution coefficients will therefore depend on the national industrial context and the actual wood use practices, and are likely to change over time according to business strategy (upgrading of processes and supply basins), consumption patterns and changes in the end uses of wood products.

Two main types of substitution can be distinguished:

– **energy substitution**, which corresponds to the quantity of CO_2 emissions saved by using wood energy instead of reference fossil fuels such as fuel oil, gas, coal, electricity or the national energy mix (Oliver *et al.*, 2014);

– **material substitution**, which corresponds to the amount of CO_2 emissions avoided by using a wood product rather than another reference product (concrete, steel, plaster, aluminium, etc.). This use of wood as an alternative to competing materials and processes avoids significant CO_2 emissions (Eriksson *et al.*, 2012).

An analysis of available scientific knowledge provided information on the methodologies used to estimate substitution coefficients in different countries, including the specific methods, assumptions, and values obtained (for more details, see Roux *et al.*, 2017, Annex 4). The choice of substitution coefficients to be applied to the French national context considered the nature of the products used in France and the efficiency of the processing techniques highlighted in this up-to-date review.

Wood energy substitution

A primary use of wood as a substitute for other products is to burn it in place of fossil fuels. For the estimation of energy substitution coefficients, we relied on the work of Oliver *et al.* (2014), which evaluates the emissions avoided by burning wood as a substitute for gas, fuel oil and coal. We considered that in France, hardwood timber would mainly be consumed in already-existing boilers within individual houses or collective boiler rooms, and that 80% of this wood would replace fuel oil, with 20% replacing gas (no replacement of electricity). Under this assumption, an 80-20% fuel-gas mix can be applied according to three levels of infradensity selected for hardwoods. In terms of CO_2/m^3, the energy substitution coefficient therefore varies from 0.37 to 0.64, with a midpoint of 0.5 (Table 1.5).

Wood material substitution

The identification, from the international literature, of material-substitution coefficients relevant to the French context was based on the meta-analysis of Sathre and O'Connor (2010a and 2010b), using 28 of the 36 studies that were studied. Hence, 6 studies comparing wood construction to steel construction were excluded, as were 2 studies presenting abnormally high values. However, we retained the values of studies comparing utility constructions made of wood rather than metal, such as power line towers.

Table 1.5. Coefficients and assumptions for estimating the wood material and wood energy substitution effects.

Variables and coefficients		Sources
Availability/harvest of lumber, pulpwood and energy wood		Volumes from the IGN's MARGOT modelling tool (from 2015-2050)
Breakdown by use between lumber, pulpwood and energy wood		Breakdown by usage type from the FFSM model data
Substitution coefficient for lumber and pulpwood	1.6 tCO_2/m^3 Range: 0.59-3.47	Sathre and O'Connor, 2010b
Substitution coefficient for energy wood	0,5 tCO_2/m^3 Range: 0.37-0.64	Oliver *et al.*, 2014
Processing efficiency for lumber, pulpwood and energy wood		Expert opinion (current carbon balance) Data from the FFSM modelling tool (carbon balance for the period 2015-2050)

Average substitution coefficients from the study by Sathre and O'Connor (2010b), expressed in tC/m^3 were converted to tCO_2/m^3 of output using three infradensity levels and three levels of carbon content in wood, in both cases taken from the literature. Since the construction sector overwhelmingly uses softwood, we used the corresponding infradensity range from the most up-to-date international knowledge 0.36 to 0.44 t/m^3). Expressed in tCO_2/m^3 of output, the coefficient for material substitution therefore varies between 0.59 and 3.47, with a central value of 1.6 (see Table 1.5). The variation in the wood-material substitution coefficient is thus very wide, indicating a marked uncertainty as to the value (or values) that could be assigned to them. As noted above, this variability is explained by:

- the measurement uncertainties inherent in the analytical methods used in this type of approach;
- the diversity of wood products likely to be used;
- the differing performance levels of the production technologies used in relation to competing materials.

In addition to these three sources of uncertainty regarding substitution coefficients under current production and consumption conditions, when we attempt to project the sector's carbon balances into the future, further strong uncertainties of a different order will emerge. These relate to potential changes in the products likely to be consumed, and changes in the technologies that will be used to obtain both wood and alternative products.

It is important to note that, in the present study, the emission savings from wood use are partly based on the optimal carbon efficiency associated with the use of wood (compared to its competitors) and partly on the fact that the by-products (and, in certain cases, end of life products) are used to produce energy. As a result, Sathre and O'Connor's coefficients combine, under the term 'material substitution', substitution benefits that other studies would divide between materials on the one hand, and energy on the other. This study does not attempt to make such a distinction, for two reasons. Firstly, the 36 studies compiled and analysed by Sathre and O'Connor are diverse and not equally comprehensive in their coverage of the relevant production processes (reducing the number of cases to below 30 would further reduce confidence in the results). Secondly, in terms of how they are used, there are differences (which are the subject of debate) between the energy wood produced from by-products and end of life wood, and the fresh biomass used directly as energy when it leaves the forest. As a result of this choice, the quantity of wood energy from co-products was added to the biomass directly from the forest to estimate the supply of energy, but only the latter was used in calculating emissions avoided by energy substitution (to avoid double counting). One consequence is that, in the present study, the relative contribution of material *versus* energy substitution effects is clearly more to the advantage of the former, in comparison with other studies with different accounting methods. This accounting approach emphasises the added value offered by the products and by-products of timber harvesting in the substitution effect.

Our choice is justified, particularly if one considers that a large proportion of wood energy resources are constrained (the availability of pellets is a direct result of sawmilling activities, the availability of wood pieces from the branches of hardwoods implies a solvent market for large logs etc.).

Chapter 2
The current carbon balance across the French forestry & wood sector

An already significant carbon balance

Based on the coefficients and assumptions previously identified, it is possible to establish the current carbon balance of the French forestry & wood sector and the breakdown of each of the four forestry mechanisms that can influence CO_2 emission mitigation. Reconciling the following calculations with the national accounting results produced by the Technical Reference Center for Air Pollution and Climate Change (CITEPA) is difficult, as accounting practices differ. Rather than focusing on absolute values, we are more concerned with highlighting the orders of magnitude differences between the different contributors to the carbon balance, as well as their possible changes under different management/mobilisation scenarios.

Figure 2.1 presents the material flows between the different segments of the French forestry & wood sector (in Mm^3/year) and the annual CO_2 flows related to the mechanisms identified in the study (in $MtCO_2eq$/year). It is based on the storage coefficients, substitution coefficients, and assumptions presented in Chapter 1, and uses the midpoints of the ranges of coefficient values (Tables 1.1 to 1.5).

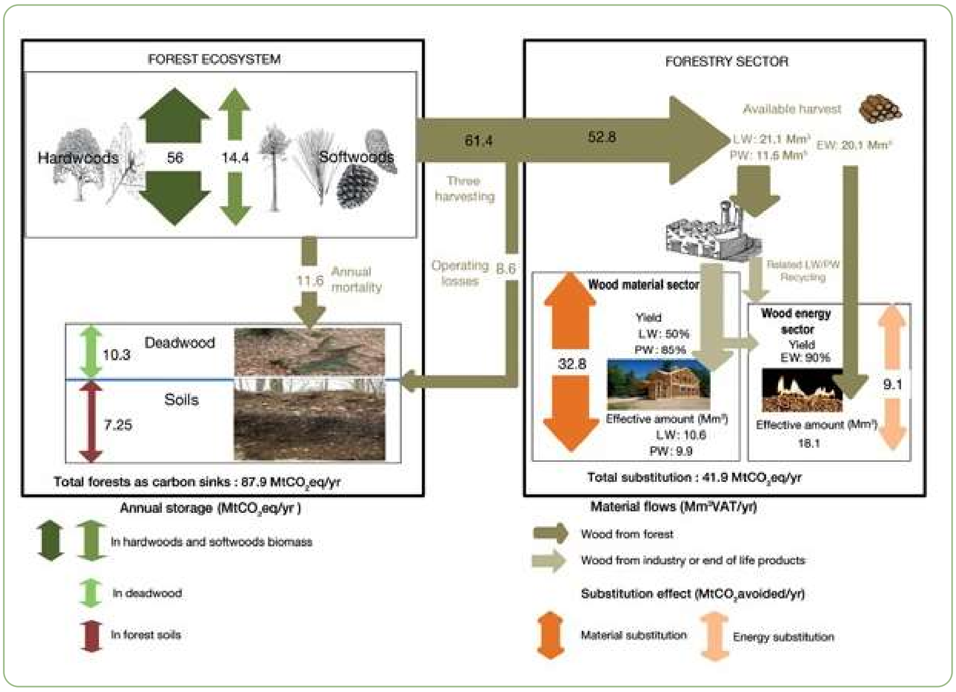

Figure 2.1. Material and CO_2 flows through the different segments of the French forestry & wood sector in 2013.

The values presented in this figure were calculated in 2015 and reflect the available knowledge at the time.
TAV = Total aerial volume, LW = Lumber, PW = Pulpwood, EW = Energy wood

Storage in the forest ecosystem (total forest ‘sinks’) and in wood products[9], as well as the substitution effects by downstream sectors (total substitution) were thus estimated. Under this set of assumptions, the carbon balance of the French forestry & wood sector can be assessed by summing the annual carbon sequestration in both the forest ecosystem and wood products and the CO_2 equivalents of GHG emissions avoided by substitution effects (material and energy), which equates to approximately 130 $MtCO_2$eq/year.

Due to the significant gap between accumulation and removal, this balance is currently dominated by annual carbon storage in forest ecosystems, forming a huge national forest carbon sink of approximately 88 $MtCO_2$eq/year. This total is dominated by carbon storage in above-ground hardwood biomass (56 $MtCO_2$eq/year) while storage in above-ground softwood biomass (14 $MtCO_2$eq/year) is in the same order of magnitude as in dead wood and soils (10 and 7 $MtCO_2$eq/year, respectively). Although impossible to measure, it should be noted that all of these values carry uncertainties related to the accuracy of the IFN data used as inputs, the models employed, and the variability of conversion factors, particularly when converting from volumes to biomass. The CO_2 balance in forest biomass is also sensitive to the calculation method that compares, for a given year, biological production and wood removals, although over an annual time step these two terms are not driven by the same dynamics. In the CITEPA inventory, the interannual variability of the CO_2 balance of the biomass is between 5 and 15%.

The estimate of current carbon storage in dead wood also suffers from an unquantifiable but significant degree of uncertainty. In fact, the variation in the stock of dead wood in forests, as measured over the past ten years, does not show such a strong storage trend. When estimating the degree of decomposition of dead wood, site conditions and the type of dead wood should be considered in combination.

While research is currently underway to quantify and reduce uncertainty, the trends remain valid because they are observed over long time series.

The amount of carbon in wood products is currently assumed to be zero, meaning that the carbon stored in the year’s production equates to the removal of carbon from storage at the end of its life and the destruction of previous wood products. Thus, the current favourable effect of wood usage in the sector is based solely on substitution effects, including wood-material substitution which, at 33 $MtCO_2$eq/year and even taking into account the wide range of variability within the substitution coefficient, appears to be an important mechanism for mitigating climate change by avoiding greenhouse gas emissions from competing products.

The substitution linked to wood used directly for energy, despite the large volumes used (20 Mm^3/year, or 40% of the harvest), is currently responsible for a small share of the carbon balance of French forests (9 $MtCO_2eq$/year). This low value is partly due to the assumption whereby the substitution effects of energy use generated by the combustion of end-of-life wood products are recorded as wood-material effects.

In addition to the assumptions and coefficients discussed in Chapter 1, two important conventions were required to develop the balance sheet shown in Figure 2.1. The first concerns the use of lumber and pulpwood sourced from the forest, with yields estimated here at 50% and 85%, respectively[10]. These coefficients do not include operating losses, which are estimated to be significant (14% of the harvested volume), and collectively include debris, incidental mortality and the fraction of the resource left in the forest. On the other hand, yields include material wastage along the transport and processing chain, as well as the allocation of a portion of the pulpwood to the paper industry. The second convention assumes foreign trade to be carbon neutral. Thus, the volume of logs harvested for export is not subtracted from the carbon balance, while imported forest products used in secondary processing are also excluded, since the carbon balance associated with these two activities is assumed to be relatively small. These two conventions clearly warrant testing. This type of sensitivity study would be appropriate in the context of a comprehensive modelling of flows and storage in the various processing stages of the sector, for which, as will be shown later, the tools are currently lacking.

Factors affecting the carbon balance: forest management, climate and risks

Impacts on forest dynamics and wood usage

Given the respective contributions of the drivers of the current carbon balance of the French forestry & wood sector, the future management of forestry will clearly have a direct impact on this carbon balance. This occurs via, on the one hand, impacts on stand dynamics, and therefore the storage or release of carbon, and on the other hand, the sector's ability to market products with high substitution rates compared with competing sectors that emit more greenhouse gases. Maintaining current harvest levels in a context of growing standing stock would allow increased carbon storage in forests (at least as long as these relatively young forests are rapidly growing) but would also limit the substitution effects expected from the expansion of wood use. However, this strategy of limiting harvest levels could result in greater sensitivity to climatic hazards and various other major disturbances that could impact French forests. Conversely, a more intensive harvest combined with management to improve productivity would, at least temporarily, slow the increase in the carbon stock in forests, but facilitate increased substitution effects after harvesting, particularly if wood is used as a material.

These different management approaches would differentially effect forest tree demographics, with mortality, recruitment and growth rates all reflecting the intensity of competitive processes. In addition, changes in species composition, and the success of newly established populations and varieties will affect the storage of carbon. By 2050, changes in the demographic structure of forests will, in principle, have the greatest impact, while conditions for regeneration will play a greater role during the decades following this short time horizon (adaptability of genetic resources, ability of existing stands to maintain productivity under increasing climate pressures, etc.).

While forest management options can strongly affect the carbon balance of French forests, several key disturbance factors, such as ongoing climate change or extreme events, could severely reduce carbon storage in forest ecosystems and drastically change the sector's carbon balance. Therefore, contrary to many studies carried out to date, this study attempts to take into account the consequences of climate change on forest stands and their impact on the carbon balance of the sector over the coming decades. Similarly, certain extreme events (drought, fires, storms), or disturbances such as severe biological invasions affecting all or part of forest stands, are likely to seriously disrupt the strength of the national forest sink. The frequency and intensity of some biotic and abiotic hazards could also increase as a result of climatic disruptions, thus aggravating forest damage. This issue underlies the scenarios presented in order to study changes in the carbon balance of the sector up to 2050. As explained below, these scenarios are based on changes in forest management, climate change and major environmental disturbances.

Impacts on calculation coefficients and assumptions

Analysis of the current carbon balance reveals that storage in forest ecosystems, particularly within hardwood biomass, along with material substitution effects, are the two most important contributors to this balance. Nevertheless, their estimation through to 2050 is subject to certain limits and uncertainties due to the tools available, but also to the possible changes in the coefficients and assumptions used in the analysis, which will vary depending on management options and changes in the climate.

Projections of future French forest resources (e.g. standing timber stocks, availability and mortality), are made using the IGN's MARGOT resource model. However, the forests of metropolitan France are characterized by great diversity among stands and forestry contexts. Moreover, for several decades they have been in a state of 'forest transition', whereby agricultural decline has led to strong forest expansion and accumulation (IGN, 2013). Climate change, by affecting environmental conditions, also affects tree growth, as well the occurrence of extreme events. In this varied and dynamic context, detailed and extensive IFN data is required, as well as models able to express the dynamics of heterogeneous forests in a non-steady state in order to simulate the changes in French forest resources. The 2050 horizon is clearly too distant for us to assume stationarity of the transition matrices. However, as will be shown later, a major limitation of the MARGOT model lies in the difficulty of correctly simulating changes affecting the resource, whether they are extreme and rapid (e.g. linked climate effects or extreme events) or gradual (e.g. those induced by a progressive densification of the stands).

Given the relative importance of substitution effects, notably as regards wood materials, the carbon balance of the sector by 2050 will depend, on the one hand, on changes in the management of the forestry & wood sector industries (product mix, efficiency of the various processing methods, recycling rates and the fate of end-of-life products) and, on the other hand, on their relative position in the national production chain and their technological performance compared to competing industries.

Aside from the dilution effects (the comparative advantage should drop when market share changes from 5% to 25%), specialisation driven by scarcity may occur (reserving the use of concrete, metals and wood for situations in which their efficiency is maximized). The impacts of changes in the national energy and electricity mix on the relative performance of different materials also cannot be avoided. Regarding material substitution coefficients, 11 of the 21 articles compiled by Sathre and O'Connor (2010) concern Sweden, Norway, Finland and Switzerland, which have energy mixes close to that of France, while the other references concern countries with high greenhouse gas emissions such as the United States. The trajectories of these production systems between now and 2050 are marred by hazards and uncertainties, as shown by Germany's difficulty in meeting its 2020 target (Beeker, 2017). The simulations for the period up to 2050 presented in this volume assume a constant substitution coefficient for both wood-materials and wood-energy over time. This important assumption was made because it was impossible to make a comparative projection of the wood-based sectors and their competitors, or of the electricity and energy mix as a whole. Such an exercise in technological forecasting would require the use of multiple assumptions and specific scenarios, which could not be conducted in the context of this study. In effect, the substitution coefficients would change concurrently under the effect of three components: the composition of the wood products consumed, whose substitution coefficients may differ markedly from what is retained here; wood processing technologies and their energy consumption characteristics; and the evolution of production technologies for competing products and their characteristics in terms of greenhouse gas emissions. There are suggestions that concrete or metal industries may seek to green their processes (e.g. by energy substitution within their production processes); *conversely*, the new sustainability challenges faced by these industries are expected to increase their energy costs (e.g. sand availability). It is therefore clear that adjusting the substitution coefficients upwards or downwards would be particularly challenging, and that a rigorous analysis in this area would need to consider different technological options: the capacity to reduce emissions through incremental or radical innovation, or the use of more renewable energies. Such an approach would inevitably lead to several scenarios for changing substitution coefficients, based on specific technological grounds.

Similarly, a better representation of the use patterns (energy wood, pulpwood, lumber) and how these might change under different scenarios is also necessary, both for the assessment of substitution effects and for the estimation of storage in wood products. Indeed, over the past ten years or so, there have been major changes in the way wood categories (species*size) are processed by the various industries. The ratio between energy and lumber use for beech in Germany has rapidly changed in favour of energy.

Conversely, new reconstituted wood processes allow small diameter logs that would have been consumed as pulpwood to be converted into lumber. The implications of these developments on storage in wood products and on substitution effects will be discussed further in this book. Thus, estimates of change in harvest use between now and 2050 (currently estimated at 38% for energy wood, 28% for pulpwood and 34% for lumber) would benefit from more explicit modelling, e.g., an optimal calculation that matches supply and demand in the sector and that can evolve over time horizons such as 2050.

Conclusion of Part I

The review of the literature and compilation of the resulting information into a current carbon budget for the French forestry & wood sector, as presented in this first section, has confirmed the role played both by forest ecosystems and the use of wood products in mitigating the greenhouse effect. It has also enabled both the refinement of the assumptions and coefficients relating to storage and substitution in the French context, and the identification of the sources of uncertainty that may impact certain key parameters.

With 130 $MtCO_2eq$ sequestered or avoided each year, the French forestry & wood sector plays a significant role in mitigating climate change[11]. This compensation corresponds to approximately 28% of annual greenhouse gas emissions in France, or all of those emitted by the transport sector (Citepa, 2018 emissions data). This balance is currently dominated by storage in forest ecosystems, which we estimate at 88 $MtCO_2eq$/year, with the greatest contribution to storage coming from above- and below-ground biomass within hardwood stands.

Annual sequestration in wood products is, in the present study, taken to be zero, meaning that the amount of carbon sequestered in production in a given year will be equal to removal at the end-of-life and destruction of previously-manufactured wood products. The favourable effect of wood use is therefore solely based on substitution effects, with the major effect coming from wood-material substitution (32.8 $MtCO_2eq$/year according to our assessment), since substitution linked to energy use contributes only slightly to the carbon balance of the sector.

It should nevertheless be remembered that all carbon balance values contain a degree of uncertainty, which is often difficult to quantify. This may relate to the accuracy of the inventory data, the models and conversion coefficients used, and the interannual variability of the climate and, *ultimately*, of the CO_2 in biomass. In addition, changes in the carbon balance over time will depend on other variables. Storage within the ecosystem will depend on the demographics of forest stands, which is linked to changes in society's demand for wood products, the choice of species and varieties used to restock, the increasing numbers of extreme disease or climatic events, and the resilience of stands in a changing environment. Uncertainties in substitution coefficients will arise mostly from factors such as the types of wood products being produced, and the technologies used to manufacture them as well as their competing products.

Throughout the remainder of this study, since it was not possible to include the numerous uncertainties in factors, we focused on just two aspects that could significantly affect the future of this resource and consequently its contribution to carbon storage:

– forest management and those involved in wood processing who, in their respective roles, could influence the mechanisms for mitigating CO_2 emissions in the forest sink, wood products and the substitution effects resulting from the use of wood products;

– the intensification of climate change and its effects on forest dynamics, in the form of reduced production and increased mortality, but also in the form of extreme biotic or abiotic events, which may increase in frequency and intensity, thus disrupting the expected gains from carbon storage in the forest ecosystem.

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6 Complete reviews of the international scientific literature relating to each of the mechanisms are available in Roux *et al*. (2017, Annexes 2, 3 and 4).

7 ICP Forest Level II is an intensive monitoring network comprising permanent plots distributed throughout the main forest ecosystems in Europe. Its purpose is to detect changes in the functioning of forest ecosystems and the impacts of climate change, and to better understand the reasons for and consequences of these changes, in particular on nutrition, tree resistance, soil fertility and, more recently, on biodiversity.

8 The Soil Quality Monitoring Network (RMQS) is a long-term soil monitoring program. It involves the monitoring of 2,240 sites evenly distributed throughout France (metropolitan France and overseas territories), based on a 16 km × 16 km grid. Soil samples, measurements and observations are collected every fifteen years. The second cycle of monitoring is currently under way.

9 Storage in wood products absent from Figure 2.1 as it is assumed to be currently equal to zero.

10 Revisions of these values are in progress, with the aim of better distinguishing between the types of wood products.

11 Forestry activity also emits greenhouse gases, e.g., during forest management, logging and wood utilization operations. These emissions are low in relation to sequestration. Whether they should be more explicitly included when calculating the net contribution of forestry activities to the carbon balance is currently under discussion.

Part II

The carbon balances and economic effects of three forest management scenarios until 2050

Our approach to assessing the carbon budget of the French forestry & wood sector was designed to be applied for projections up to 2050. Three forest management scenarios were developed in order to contrast the methods by which the different CO_2 mitigation mechanisms relating to the forest sink, carbon storage in wood products and the substitution effects induced by the use of these same wood products can be implemented. None of these management scenarios are intended to explicitly represent specific public policy or sectorial strategies such as the National Forest and Wood Programme (PNFB), even though there may be similarities. As in any prospective approach, the aim is to provide the opportunity to explore as wide a range of possibilities as possible, without presupposing one or more scenarios that are desired or desirable for a particular stakeholder.

After presenting the rationale behind the three selected forest management scenarios, and detailing the reforestation plan proposed in one of them, we present the views of sectorial stakeholders to whom the scenarios were presented in order to discuss their plausibility and to highlight the obstacles and opportunities in each. We then explain the approach to forecasting for the various components of the sector in order to establish changes in the annual carbon balance for each of these three scenarios until 2050. Based on the MARGOT projection model developed by the IGN, this part of the study does not consider the effects of future climate change, i.e. it maintains the climatic conditions of recent years across the entire 2016-2050 period. The analysis and discussion of the results are supplemented by an analysis of the economic challenges to be met in order to implement these strategies using the FFSM economic model.

Chapter 3

Three forest management scenarios to the year 2050

In order to examine possible changes in the carbon balance of the sector up to relatively distant horizons such as 2050, it is necessary to set the trajectories for resource management and use. Prior to the development of these management scenarios, a number of factors were considered.

They relate to the supply/demand imbalance between hardwood and softwood, the levels of harvesting and sawn timber production, the geographical heterogeneity of harvesting rates, marketing methods (sale of standing timber versus roadside supply contracts or delivered to the mill), the degree of harvest mechanisation, the impact of sawing processes on value creation, the increase in the stock of large and very large timber, the planting of seedlings, the density of large ungulates, etc.

We also drew from a study carried out in France to identify prospects for the further exploitation of hardwood resources (FCBA, 2011) and from the European SCAR-4 forward-looking study on the development of the bioeconomy (Mathijs *et al.*, 2015). Our three management scenarios (‘Extensification and reduced harvesting’, ‘Territorial dynamics’, ‘Intensification and increased harvesting’) fall within the broad context considered by the FCBA report (2011): moderation of economic growth, structural demographic change (ageing), expansion of environmental objectives (whose priorities may vary between the pursuit of naturalness, renewable energy and damage prevention), globalisation of trade, progress in energy recovery, and abundance of hardwood resources. However, while the FCBA study used only two scenarios (marginalization of hardwood forest versus a dynamic and competitive hardwood sector), we opted here for three scenarios, in line with the division of the SCAR study (A: moderation; B: abundance; C: rarity).

The drivers that differentiate these three hypothetical management scenarios are, on the one hand, the willingness of the various stakeholders to invest in forests and, on the other hand, the industrial future of French hardwood resources (see Table 3.1 for a summary of the scenarios). The willingness to invest depends on economic conditions (price/cost in apparent values, including taxation, subsidies, labour costs, etc.), but probably also on subjective values related to the ways in which sustainability and multifunctionality are represented. The valorization of hardwood resources has many technological, regulatory, economic, social and silvicultural aspects. It will have a critical effect on the entire forestry & wood sector, given the current very pronounced decline in national processing capacity, and the ripple effect that would result from a reversal of this decline in the past 30 years.

Table 3.1. Summary elements of the resource management and utilization scenarios.

Scenario elements	Extensification and reduced harvesting	Territorial dynamics	Intensification and increased harvesting
Implementation of sustainable forest management	Large areas free to evolve naturally + silviculture close to nature	Prevalence of natural regeneration, alteration after major disturbances, game highly constrained.	Management of game, shorter operating ages, species changes, planting, soil improvements.
Ways of adapting to climate change	Passive: confidence in the system's ability to adapt spontaneously and to drive natural processes	Reactive/passive: adaptation decisions are taken after major disturbances, or they are left alone (depending on the intensity of regional management)	Proactive: planning and adaptive management (diversification, visible and deliberate transformations, search for resilience *via* production systems)
Land use regulation	Modest expansion of protected areas	Supply contracts for communal forests in the East and private forests in the Massif Central, adaptation of Natura 2000 to climate change	Collective management, contractualization, public-private partnerships, adaptation of Natura 2000 to climate change
Variation between regions	Massif Central under management, minimal management in high mountains and Mediterranean regions	Strong divergence in options and investment; high mountains and Mediterranean regions remain extensive	Resumption of partial management of all mountain ranges, and of energy wood and pulpwood production in the Mediterranean sector
Expansion of the forest area	Moderate rate (40,000 ha/year), only as spontaneous natural expansion	Moderate rate (40,000 ha/year), some localized plantations	Moderate rate (40,000 ha/year), in addition to new plantations: + 50,000 ha/year for ten years (see reforestation plan)
	Maintain at 2015 level in absolute	Maintenance of harvest	Moving towards an increase in harvest

National harvest level	value (volume harvested, national total for all uses), or ≈50 Mm^3 TAV/year	rates, ≈50 % net increase (rising to 70 Mm^3 TAV/year by 2050)	rates of 70 to 75% of net growth, i.e. 90 Mm^3 TAV/year by 2050
Harvest allocation between uses	Shifts in use: continuation of the trend towards the ‘nibbling’ of large diameters through wood-energy markets	Heterogeneous depending to regional policy decisions, allocation driven from downstream (pulpwood penalized compared to energy wood)	New processes to add value to hardwoods, extension of dedicated forests, supply contracts balancing the supply between lumber, pulpwood and energy wood
Wood energy	Moderate increase via imports (limited local supply)	Strong increase (heating networks)	Very strong increase (heat + cogeneration + 2nd generation biofuels)
National industrial fabric	Further weakening of hardwood sawmilling, national processing concentrated in a few industrial sites with large supply areas	Medium to large companies, slight increase in the number of forestry cooperatives but unevenly between territories, gradually-increasing supply of energy wood and pulpwood with harvest surpluses	Transition to new hardwood industries Development of 2-3 new sub-sectors to add value to resources, transformation structured around large manufacturers and SMEs, strong growth in forest cooperatives
International Trade	Export of high-end hardwood logs, imports (chips, sawn timber, pulp, panels, furniture), very large trade deficit	Fewer hardwood logs for export, large deficit in softwood sawn timber, large trade deficit	Moderate trade deficit to compensate for supply/demand mismatch (hardwood/softwood) + furniture
Forestry investment	Renewal of existing coverage, minimal forestry operations in productive areas or areas of high fire risk	In some regions, increased coverage, silvicultural operations, compartmentalisation, protection from game	Development of digital tools, doubling of mountain coverage, mechanisation (hardwood + mountain), silvicultural operations, planting, recycling of boiler room ashes
Investment in training	Maintaining the current training framework	Higher priority on commercialization, forestry operations, mechanization	Extensive change: digital, planning, logistics, operations, commercialization, mechanization, upstream-downstream integration, optimizing the value chain
Carbon sinks:	Rapid accumulation, intensification of forest carbon		Slowing of forest carbon storage: it

expected changes	storage (in a 1st phase), with subsequent changes linked to damage	Moderate accumulation	will be lower than its 2015 value
Effects on forestry plantations	Almost imperceptible (except in Aquitaine)	Moderate: In Aquitaine, transformation of public lowland forests, some experimental plantations in the search for solutions for adaptation to climate change	Strong: proactive transformations, spread of high productivity plantations (softwood, poplar, eucalyptus), reintroduction of hardwood and softwood forests in the mountains
Expected impacts of forest damage	Background mortality changes as stands age + dead wood & fuel + dieback due to poor adaptation + diseases (e. g. ash dieback)	Rise in background mortality + decline due to poor adaptation + disease outbreaks (e. g. ash dieback)	Regeneration of declining stands + diseases outbreaks related to the artificialization of stands (e. g. red band needle blight in pines) Mitigation of fire & storm risks

VAT: total aerial volume

‘Extensification and reduced harvesting’ scenario

In this scenario, social pressure for ‘wildness’, and little incentive from prices or public policies on both processors and foresters, will encourage further extensification or even abandonment of management for parts of forests. These processes, already well underway in high mountains, will gradually extend to large lowland and moderately mountainous areas where small private or communal forest holdings have little capacity to cope with climate risks. Local industrial weaknesses, reinforced by the preference for the sale of high-end logs on international markets, would directly contribute to the socio-economic and organizational vulnerability of the sector both locally and nationally.

The natural attributes of forests would be significantly enhanced, with vast areas of forest in a state of natural succession. These areas, which are poorly or completely un-equipped for silviculture, would be subject to sporadic harvesting. The increasing frequency of damage to unharvested wood (parched trees, windfall, insect infestations, etc.) would lead to an accumulation of dead wood. The expansion of the area under forest would occur at a moderate rate (40,000 ha/year), but solely from natural increases. Forests in high mountain areas and in the Mediterranean region would be subject to minimal management (statutory clearing in areas at risk of fire), while some forests in the Massif Central will remain under-exploited.

At the same time, a minority of forests (30 to 40% in surface area) would still be managed for wood production. These include state-owned forests, communal forests in regions where the tradition of productive forestry continues (particularly in the north-east), large private forests, and the Landes forest, which adapts to climate damage and continues its unique, tight integration between forest and industry. Other than in Landes, the dominant practice would be based on natural regeneration and the search for niche export markets on the basis of harvested wood products.

The approach to adaptation to climate change would primarily concern existing protected areas, but with a moderate extension of their network. Beyond that, it is mainly passive: silviculturists will not undertake transformation work due to their confidence in the adaptive capacities of forest ecosystems and natural dynamic processes. The lack of suitable machinery and the low propensity to open up logging partitions constrains the mechanisation of hardwood harvesting. The argument that the transformation of forests by ‘agronomic’ methods in the post-war period was responsible for the current vulnerability of forests often rationalises the (partly forced) choice to avoid forestry operations and investments.

Over the projected period, the national harvest level[12] will remain close to the current level (2016) in absolute terms, i.e. approximately 50 Mm^3 TAV/year (volume harvested, national total for all uses). Hardwood uses will continue to shift towards the wood energy market, supplementing the small export market for high-end logs.

With the continued weakening of the hardwood sawmilling industry, national processing will be concentrated on softwood resources and conducted by a few industrial sites with large supply ranges. Progress in the bioeconomy will be fuelled by imports of wood chips, sawn timber, pulp, board, and furniture, which widens the trade deficit in the forestry & wood sector. Investment will focus on the renewal of existing supply, with the limited silvicultural activity restricted to productive areas or areas at high risk of fire.

Given the lack of active management characterizing most forests under this scenario, we expect, initially, a continuation or acceleration of the rapid forest accumulation observed over the past 30 years, with a consequent increase in the carbon sink as reported by France in accordance with the United Nations Framework Convention on Climate Change. After a few decades, the slowdown in forest growth linked to the ageing of existing stands, the resurgence of climate change-related disease outbreaks, and the sector's limited capacity to respond (low harvesting and storage, renewal through natural regeneration) could lead to a less favourable trend in available wood resources.

An intermediate 'Territorial Dynamics' scenario

We envisage, in this scenario, a trajectory of reactive change in stages, where sectoral stakeholders and forest policymakers rely on crises to induce changes that lead to diverging trajectories between territories, with a strong guiding role played by the new large regions that replace the State as a framework for collective action.

In a context of strong social and economic change (search for local energy independence, development of agro-ecology, reintegration of urban areas into productive systems – particularly agricultural), forestry professionals will be 'drawn' to other business sectors that require and enhance their skills more than the forestry sector itself (agroforestry, ecotourism, urban ecology, circular economy etc.). Due to this external competition, the strength of demand for biomass (trends are driven by sectors outside the forest sector) will be the driving force behind this scenario, especially for energy and associated with low prices. This in turn will lead to a simplification of management practices and a specialisation of objectives.

The forests will expand at a moderate rate (40,000 ha/year), mainly as spontaneous natural increases, but with a few large areas of replanting. Forest management will remain extensive in high mountain regions and Mediterranean regions, some (mountain) areas will continue to face the problem of forest access, while private owners in the Massif Central and communal forest regions in the east make efforts to consolidate and enter into collective agreements. The regions replace the State in the development of forest policies, choosing various options depending on local configurations (both in terms of their intended uses and financing). The supply of wood from agroforestry and dedicated peri-urban plantations will increase.

Foresters and industrialists are aware of climate risks, but the interplay of socio-economic, silvicultural and environmental constraints leaves few opportunities to transform practices as they would like (e.g. damage by game significantly constrains renewal in the sector). Combined with the high demand for biomass, the streamlining of practices and the partial regionalisation of policies, these changes will gradually increase the heterogeneity of forest landscapes, which is generally favourable to biodiversity.

Harvests will increase in a piecemeal fashion, mainly driven by salvage or protective harvests after fires, windfalls or outbreaks of pests. Taken as a whole, this trajectory could result in the maintenance of the current rate of harvest over the period (i.e. 50% of the net biological increase), with the volume harvested rising to around 70 Mm^3 TAV/year (total aerial volume) by 2050. New processes will develop in order to enhance the value of hardwood, mainly by foreign industrial groups setting up where supplies are secured by contracts (this reindustrialisation of hardwoods is therefore heterogeneous across regions). The distribution of wood between the different uses is driven entirely by the markets. In particular, pulpwood will be penalized by the high demand for energy wood to supply heating networks. The number of cooperatives will also increase unevenly between territories.

The national industrial fabric is structured by medium-sized to large companies. The export of hardwood logs will continue at a moderate rate, whilst the deficit in softwood sawn timber and, more generally, the large deficit in the trade balance of the forestry & wood sector will remain. Investment levels will be heterogeneous, with a slight expansion of supply and forestry activities concentrated in regions with a combination of downstream demand and local policy measures.

'Intensification and increase of harvests' scenario

A favourable context for increased harvests

In this case, the economic and political environment would strongly favour a profound transition for French metropolitan forests because:

– on the one hand, hardwood consumption will be facilitated by a combination of technological innovations, standardised approaches, investments from foreign multinationals and/or French industrial sectors in the process of realignment, training initiatives, strong public incentives to consolidate properties and contracting, and the simplification of management practices;

– on the other hand, the economic climate would be more favourable to forestry investment, due to attractive markets and a tax system that is more favourable to climate-friendly sectors and less burdensome for labour-intensive activities.

This environment would promote more active forest management designed to address the different aspects of climate change, by enhancing the contribution to mitigation, enabling the implementation of various adaptation strategies, securing ecosystem services, and improving the ability of the sector to better absorb the shocks resulting from extreme events.

The use of forest land will change as a result of organisational innovation: collective management of large areas (including composite areas that combine both public and private property), significant expansion of contractual agreements (hunting, marketing, sustainable management assessment, specific biodiversity measures), and adaptation of Natura 2000 objectives to the climate change context. Mountain forests will partly return to management and, in some cases, be restored (as in high mountains), while Mediterranean forests will supply more energy wood, pulpwood and sawn softwood. Spontaneous natural forest expansion will also occur at a moderate rate (+40,000 ha/year), to which is added a significant proportion of plantations on areas already forested but not very productive, the objective being a reforestation plan of 500,000 ha spread over the first 10 years of the period.

Silvicultural management methods would be marked by a reduced age of harvest (risk reduction and adaptation to processing techniques that are suited to smaller diameters), increased use of planting as a method of regeneration, regular application of soil improvers and the restoration of the balance between forest and game. The control, reorientation and continuous monitoring of plant material are becoming important markers of sustainable management: this not only concerns improved varieties, but also assisted migration practices, the introduction of new species and varieties offering a good performance/resistance trade-offs, and the conservation of genetic resources coordinated at the European level. The application of silvicultural guidance is facilitated by group management procedures. Forest plantations will have a strong impact on total production in both quantity and quality in the long term (i.e. beyond 2050), through the spread of highly productive varieties (coniferous, poplar, eucalyptus), resulting from breeding programmes that are redesigned in a context of interactions between climate change impacts and the bioeconomy.

In this scenario, the approach towards climate change would be mainly proactive, with diversification of options, transformations, the pursuit of organizational resilience through production systems, and the revival of planning and monitoring. To boost the contribution of forests to mitigation, a programme of high-productivity plantations (detailed below) would be implemented, and we would see a sustained development of short-cycle, industry-oriented forests both in the Landes forest and in other regions where these strategies contribute to the diversification of forest species and age classes.

The national harvest will gradually increase to 90 Mm^3/year (total aerial volume) by 2050, which could equate to 70-75% of the net biological increase by that time. The exploitation of hardwoods would develop around two or three new sub-sectors, stimulated by a more incentive-based policy framework. Processing would be structured around large industrial groups and an emerging network of SMEs to test new processes funded through different financial channels (sponsorship, crowdfunding, etc.). New products and constructive solutions mixing hardwood and softwood will also be developed. Cooperatives and forestry experts will see their activity replicated in private forests, with a sharp increase in the harvesting and complete management of new group management entities. The sector would remain in deficit, but more moderately so.

The level of investment will be high, with the digitalisation of procedures, doubling of mountain access, efforts to mechanise the processing of large-diameter hardwood and softwood trees, planting, silvicultural operations, recycling boiler ash and use in soil improvement etc. The investment in training would also be significant, with efforts made to attract young people to technologies adapted to active management (planning, logistics, commercialisation, works, upstream and downstream integration, value chain optimisation, etc.).

Mortality would be mitigated by the regeneration of ageing or dying stands, and damage from fires and storms would be reduced. Disease outbreaks would be preponderant (e.g. fungal dieback on ash, red band disease on Corsican pine).

This 'Intensification' scenario, which foresees a gradual increase in harvests until 2050, has the advantage, on the one hand, of allowing industries (nurseries, primary processing in France) to gradually adapt their production capacities and, on the other hand, to avoid sudden production losses or falls in social or environmental amenities in the event of a major impact.

A reforestation plan with effects extending beyond 2050

The contribution of forests and the forestry & wood sector to the fight against climate change is the result of various phenomena, the effects of which vary according to the time scale studied. For example, the current importance of forests as a carbon sink stems from the fact that French forests are young, but in the absence of expansion of forest areas, an increase in harvesting, all other things being equal, would result in a decrease in the forest sink (but an increase in storage in wood products and substitution effects).

In view of these uncertainties, and the abnormally low rate of wood removals from forests, one of the working groups responsible for drawing up the National Forest and Timber Programme[13] proposed a scenario of gradual but continuous harvest increases, with a trajectory resulting in harvests equalling net biological production by 2100. This would equate to an annual increase of around 750,000 m^3 (with an average value that could fluctuate between 500,000 and 1,000,000 m^3).

Madignier *et al*. (2014) also proposed a stimulation of existing silviculture, but with a far more ambitious reforestation plan. These proposals aim to increase the area of productive forest and/or improve certain forest areas that are not currently economically valued through reforestation of up to 50,000 ha/year with productive coniferous species. Assuming that 500,000 ha is planted by 2030, and an average productivity differential of + 10 m^3/ha/year (compared to present levels), this afforestation and reforestation could represent an additional production of around 3 to 5 million cubic metres of wood per year, with an extra 3 to 5 million tonne CO_2 added to the forest carbon sink per year.

France has already carried out ambitious reforestation programmes on several occasions, the most recent of which is the National Forestry Fund (*Fonds forestier national*). Legay and Le Bouler (2014) report that, presently, with approximately 2 million hectares completely reforested and 1 million hectares at least partially reforested, "The human effort to create these voluntary forests has largely succeeded." Ginisty *et al*. (1998) conducted an extensive survey of the success of reforestation supported by the National Forest Fund (1973-1988). The survey revealed positive results for softwoods in general, and for maritime pine and Douglas fir in particular, as well as for poplar. Hardwoods, on the other hand, had the lowest success rates.

The option of stimulating the creation of new resources through a new programme of high-productivity forest plantations is therefore at the heart of scenarios aimed at boosting the management of forests. It is fully justified in terms of:

- implementation of sustainable forest management;
- adaptation to climate change;
- coupling harvested products to uses (including wood energy);
- competitiveness of the forestry & wood sector in international trade;
- contribution to the carbon sink.

Thus, in a context of 'Intensification', as envisaged in the third scenario, the feasibility of a reforestation plan based on the proposals made in Madignier *et al.* (2014) was examined. This analysis enabled us, in particular, to develop a strategy for a progressive reforestation of 500,000 ha over the next ten years, with an average productivity differential of + 10 m^3/ha/year compared to present levels. The objective was to produce an additional 3 to 5 million cubic metres of wood per year.

In terms of feasibility and resources, the analysis was based on three key reforestation issues: choice of species, choice of silviculture, and choice of regions in which to replant[14]. The approach taken is based on a selection of ten species. Most exceed a productivity of 15 m^3/ha/year, while some others may not always achieve this threshold but allow more demanding environmental conditions to be exploited, for example, in the Landes massif or in the Mediterranean region.

A reforestation plan of this scale, even if gradual, will require a total of approximately 60 million seedlings per year across all species, given the objectives. It has therefore been determined that most of the proposed species will be provided on a regular basis and in sufficient numbers from one or more of the current sources (seed orchards, selected stands, cuttings, etc.) through an increase in the harvesting of forest reproductive material and, for some species, through the use of imported seeds. In addition, an interview with a French forest nursery representative confirms that the French forest nursery network will be able to adapt very quickly to the production of the 60 million seedlings needed to carry out 50,000 ha of reforestation per year. Across all species, 40% of the plants (24 million) could be produced in containers and 60% (36 million) as bare rooted seedlings. The 36 million bare-root seedlings represent an additional 240 ha of nursery production. According to nursery operators, these nursery areas are available.

To ensure a productivity increase of 10 m^3/ha/year, dynamic silviculture will be required. It will often aim for rotations of well below 50 years. Depending on the characteristics of each species, one or more of the following three silvicultural programmes have been proposed:

- *conventional* silviculture: with an initial density of 1,100-1,200 stems/ha, with three or four regular thinnings prior to clearcutting before 50 years (204 stems/ha for poplar with no thinnings);
- *semi-dedicated* silviculture: with a higher initial density (1,600-2,000 stems/ha), a maximum of two thinnings with a first thinning after approximately 20 years, and a shorter rotation than in conventional silviculture. The initial products are destined for biomass production, while the final harvest provides timber and biomass;
- *biomass* silviculture: The aim here is clearly to shorten rotations as much as possible by limiting interventions for the production of pulpwood. The aim here is to reduce rotations to between ten and thirty years. This scenario includes short rotation coppices for suitable species (poplar, redwood, eucalyptus), as well as short rotations for some others (Sitka spruce, hybrid larch, Loblolly pine, Vancouver fir).

Drawing on the NFI database, the choice of areas to be reforested (500,000 ha) was directed, by decreasing priority, towards: areas in western France suitable for highly productive reforestation, areas in the semi-continental Grand East with low current harvest rates, certain areas currently unused for forestry due to the presence of pathogens (ash, chestnut, Corsican pine, etc.), areas in the Mediterranean region suitable for exploitation and, lastly, abandoned poplar groves.

In conjunction with the allocation of species in these areas on the basis of their pedoclimatic suitability, one or more silvicultural regimes have been defined for each species, and a breakdown of these regimes has been applied. Finally, the dynamics of reforestation were not considered linear; it takes into account the necessary ‘ramping up’ of the reforestation effort over the 10 years envisaged to achieve the reforestation plan (Figure 3.1).

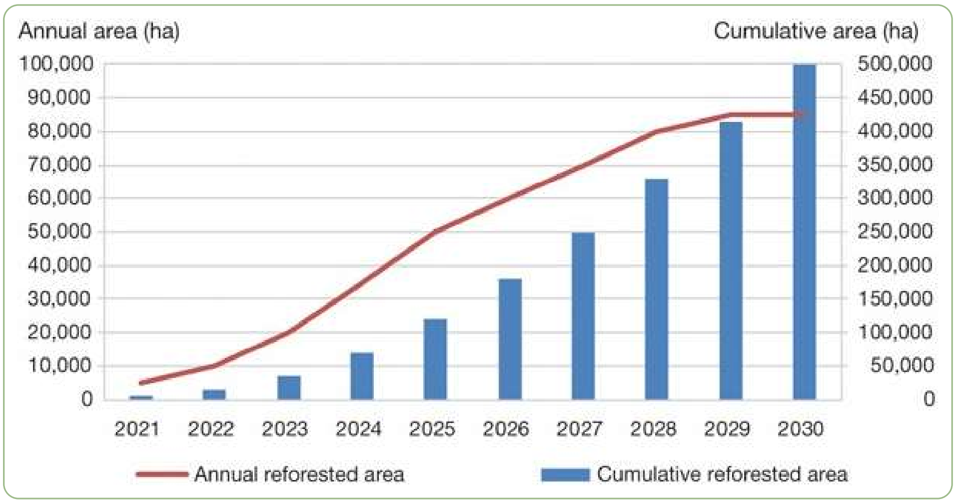

Figure 3.1. Extent of annual and cumulative reforestation from 2020 to 2030.

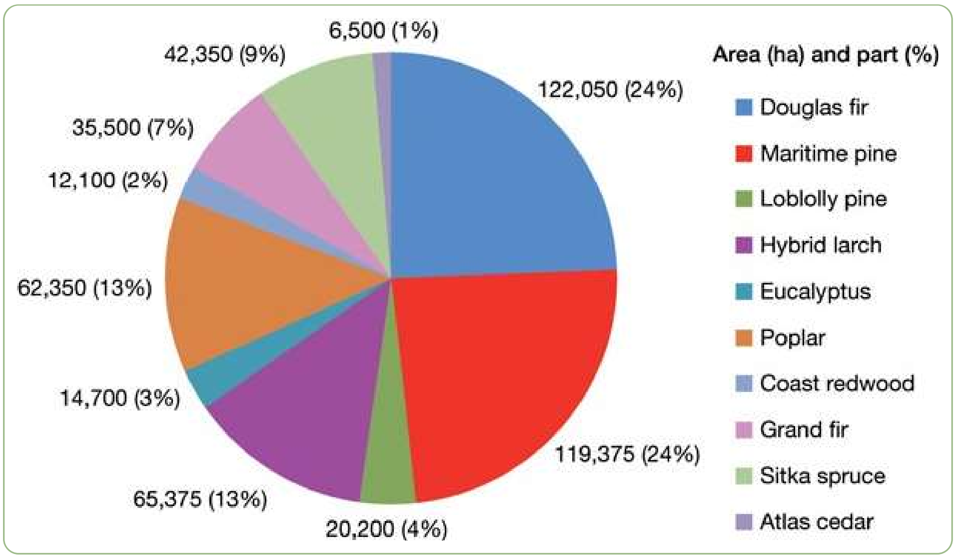

Figure 3.2. Percentage use of each species in the reforestation plan.

Ultimately, Douglas fir and maritime pine are the two main target species in terms of area reforested, followed by hybrid larch and poplar, which are of medium importance (Figure 3.2). The main focus concerns predominantly deciduous stands in the major ecological regions (GRECOs) of high priority (western half of France) and stands that are little used for forestry (84%). A significant amount, however, lies in the Eastern GRECOs (11%), while the Mediterranean region and the ‘unmaintained poplar forests’ are also included (5%).

When intrucuced into the MARGOT model (Box 4.1, p. 68), this data makes it possible to simulate the growth and removal of these forest stands over time. Figure 3.3 illustrates the effect of the implementation of the reforestation plan on wood availability up to 2100.

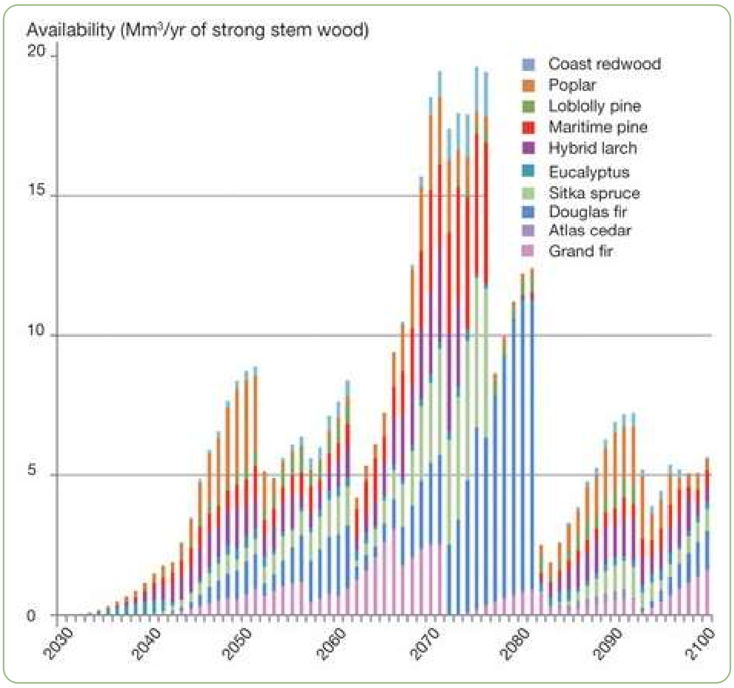

Figure 3.3. Additional wood available from the implementation of the reforestation plan, up until 2100.

It is clear from these results that such a reforestation plan will only lead to a small impact on wood availability by 2050. By this horizon, which is too soon in view of forest development processes, a slight peak in availability will be evident, mainly due to the maturity of new poplar plantations. The true peak in availability (approximately 20 Mm^3/year of strong stem wood) is not expected until 2070, when maritime pines and hybrid larch trees reach maturity simultaneously, the latter being then replaced by Sitka spruces. This peak would then continue through Douglas fir plantations but with less intensity, before a new cycle of somewhat reduced availability.

Plausibility of the management scenarios and reforestation plan

Obstacles and opportunities for the implementation of proactive scenarios, as identified by sectoral stakeholders

We presented these three scenarios to more than a dozen stakeholders from the French forestry & wood sector, and asked them to identify, for each scenario, the obstacles and opportunities for their implementation. Two scenarios were of particular interest to the stakeholders: the 'Territorial dynamics' scenario, which some considered to be akin to the continuation of the current trajectory, and the 'Intensification' scenario.

Several challenges shared by these two scenarios have been identified, including:
- a wood price offering little incentive, given the high implementation costs;
- unfavourable forest tenure and corporate structures;
- lack of access to mountainous areas, and mechanisation of hardwood exploitation is still in its infancy;
- technological barriers to the expansion of the use of wood in construction.

Conversely, some tools for implementation were frequently identified:
- education and communication initiatives aimed at encouraging and motivating stakeholders to participate, as well as at encouraging users to share their issues;
- the means to develop innovations and investments aimed at productivity gains;
- operator training;
- new public-private partnerships and new sources of funding, whether private (carbon credits, sponsorship, etc.) or public (carbon taxes, etc.);
- more efficient organisation of the sector to enable it to become more competitive, develop synergies (particularly with regard to resources), and improve services.

The obstacles specific to the 'Territorial dynamics' scenario concern the foreseeable tensions between different wood uses and the risks of competition between regions. This would require the establishment of in-depth dialogue between different parts of the sector. These would be aimed at defining and clarifying regional forest policies based on the implementation of the National Forest Wood Programme, and would help territories to organise themselves around forest resources to develop the use of wood, and recommend short-cuts to development, in particular in connection with the transition to energy.

For all stakeholders, the lack of a clear forestry policy, the difficulties in reforestation (due to issues of acceptability, land use conflicts with agriculture, the forest/game balance, the availability of businesses, costs, etc.,), and the difficulties in enhancing the value of hardwoods, all appear to be major obstacles to the development of an 'Intensification' scenario.

To remedy this, it would appear necessary to specify the key elements of a national forest policy, to develop digital and new technologies, to create new industries for hardwood forests, to develop partnerships with metropolitan areas, etc.

Benefits and limitations of the reforestation plan

The ambitious goal of the reforestation plan (in terms of both surface area and productivity) has led to the choice of fast-growing species planted in environments with few constraints (soil, slope, climate, etc.) with priority given to the replacement of stands where little wood is currently being harvested. Other undoubtedly significant areas could be developed by afforestation operations, but we have deliberately opted not to consider them here, given the expectations expressed for the reforestation plan (500,000 ha over the next ten years, with an average productivity differential of + 10 m^3/ha/year compared to present levels).

Within the areas to be forested, the issue of which of the chosen tree species should be allocated to which sites was of particular importance in this study. Regional stratification helped us to select sites based on the available knowledge for each species, although compromise between the goals of the reforestation plan and technical and economic feasibility were also necessary. Indeed, a species that has previously been rarely exploited will be difficult to exploit on a large scale within 10 years, even if its potential is known. This explains why most of the areas in the reforestation plan are made up of species that are already widely known.

Compared to current practices, the choices were made to increase planting densities and shorten rotation times. The first choice significantly increases the total production of stands and, at the same time, improves certain product characteristics (wood density, knot size). Increased densities also allow for more successful planting (dilution of game damage, faster canopy closure, stimulation of growth for height at a young age). On the other hand, this option would increase the demand for forest reproductive material. The reduction in rotation times reduces exposure to the risk of windfall and increases carbon substitution (more wood produced per unit of area and time). Similarly, shorter cycles make it possible to produce medium diameter wood that is easy to harvest mechanically and in high demand by industry. On the other hand, harvesting very young wood will require soil fertility monitoring and possible treatment with additives. The high proportion of juvenile wood and its duraminization could justify targeted genetic improvement efforts.

Beyond the ten-year reforestation plan, research and development is needed to support the long-term renewal of the plantations. In terms of genetic improvement and varietal creation, it is necessary to anticipate the forest reproductive material requirements and prepare future generations of improved varieties, not only for the main focal species, but also for secondary species for which the potential is known. It is also necessary to optimize production in seed orchards and improve the ratio of plant output to seed produced. Networking between all stakeholders in the sector (research and development, management, seed companies, nurseries) is therefore essential. Finally, innovation should also involve the planting stage (tillage, planting, maintenance).

This reforestation plan marks a genuine departure from the objectives and methods of forest management practiced over the past 30 years in a large part of the metropolitan territory. However, it has a fairly direct connection to emerging issues in the bioeconomy. The choice of species, silvicultural methods and land targets can also be seen in an integrated perspective of adaptation to climate change (increased flexibility through shorter cycles, diversification and reconversion of forests, productivity concentrated in a reduced proportion of the managed area etc.). These arguments and rationales provide the basis for a communication and education approach that would overcome problems of acceptance.

Indeed, in France, social and economic changes have profoundly shaped the physiognomy of French forests. Originally a food source for people and then livestock, it became a source of energy, particularly for the metallurgy industry. The forest is now 'multifunctional', providing a balance of economic, environmental and social functions. The issues at stake in the above-mentioned reforestation plan lie at the heart of the balance between the environmental and economic values. The study, far from ignoring them, deliberately avoided these issues, since they have been widely studied elsewhere over the last ten years (see GIP Ecofor, 2009a and 2009b). Indeed, these studies show that, in the context of forest multifunctionality, compromises are quite possible in order to implement dynamic forestry management that takes into account and enhances all environmental functions.

Furthermore, the National Forestry and Wood Programme (PNFB, Ministry of Agriculture and Food, 2017) has set out forestry guidelines to guarantee the multifunctionality of the forest through management compatible with ecosystem sustainability. Adapted and implemented in each French region in the form of regional forest and timber programmes, they are translated into recommendations for issues as varied as the conservation and rational use of genetic resources, the preservation of biodiversity corridors, the maintenance of the physical and chemical integrity of soils and the management and exploitation of forest stands. A specialised committee of the High Council for Forests and Timber (*Conseil supérieur de la forêt et du bois*) is responsible for monitoring, reviewing and assessing the environmental impact of the programme. In the regions, these functions are entrusted to the regional forestry and timber commissions, in which professional bodies, institutional representatives and civil society are involved in dialogue.

Three contrasting visions of the future

Presented here in a narrative form (typical with foresight studies), these three forest management scenarios reflect widely divergent visions of the future of the world and its societies. From this perspective, an interesting reinterpretation of these scenarios was recently presented as part of the prospective study of French agriculture and forests conducted by the General Council for Food, Agriculture and Rural Areas (Berlizot *et al.*, 2020). They propose four contrasting scenarios for 2050 in terms of opening up to the world, while taking into account innovation, citizen involvement and governance. The authors associate the 'Extensification and reduction of harvests' scenario presented here with their so-called 'Sober science' (*Sobriété savante*) future, while the 'Intensification of harvests with a reforestation plan' scenario could be associated with two somewhat different futures: 'Environmental Capitalism' (*Capitalisme environnemental*) or 'Productive renewal' (*Productivisme renouvelé*). Finally, the 'Territorial dynamics' scenario would easily fit a 'Citizens of territories' (*Citoyens des territoires*) type trajectory. These connections, although somewhat arbitrary and not explicitly stated in the General Council for Food, Agriculture and Rural Areas' outlook, are interesting because they reveal that beyond the forestry dimensions of the resource management scenarios, which are analysed in terms of their carbon balances, these scenarios are part of broader, equally divergent societal trajectories.

A similar exercise could seek to place these three scenarios in the twelve families of scenarios identified by Lacroix *et al.* (2019) from a large number of international environmental forecasts. Within this framework, these three scenarios would be attached to the so-called 'environmental priority' families. However, they rely on different societal mechanisms. While the context of the 'Intensification of harvests with a reforestation plan' strategy logically falls within the narrative of the 'Green Growth' type scenarios, the other two are a little more difficult to classify. The narrative of the 'Territorial dynamics' scenario could be likened to the so-called 'local' family, but without all of its characteristics, particularly in terms of governance. The trajectory of 'Extensification and reduced harvests' could, for its part, be similar to the family of scenarios known as 'Positive synergies', while also lacking some of the governance elements.

Chapter 4

Carbon balances of forest management strategies up to

The effects of the trajectories described in Chapter 3 on the different components of the carbon balance of the French forestry & wood sector were simulated up to 2050 using the IGN's Margot resource model (Box 4.1). This model provides results (standing stocks, availability, growth, and mortality) which, supplemented by the simple model of the dynamics of dead wood and the substitution coefficients of the different products described in Chapter 1, allow the establishment of the different carbon balance components for each scenario. These balances comprise seven components: five for storage in the strict sense[15] (in the forest ecosystem, including hardwood and softwood biomasses, dead wood, and in soils, as well as in wood products) and two for substitution effects (quantities of annual CO_2 emissions avoided by the use of wood in preference to alternative, more emitting processes for both energy and material uses). The sum of these seven components represents the cumulative balance of forests and the forestry & wood sector as it affects the atmosphere, on an annual basis.

In implementing the Margot model, we sought to integrate most of the assumptions underlying the management scenarios. However (and unsurprisingly), not all of the changes described in the management scenarios can be translated into input variables changes in the model, with only some able to be considered. A major limitation of the forecasts presented below was the difficulty, with currently available modelling tools, to represent changes in the allocation of uses between lumber, pulpwood and energy wood in a logical manner (and in line with the intent of the scenarios). The consequences of this limit on storage in wood products and on substitution effects will need to be considered when analysing the results.

Determination of harvest levels

Harvest levels are a key variable distinguishing between the different scenarios, and have been set externally and in different ways depending on the specific scenario.

The 'Territorial dynamics' scenario corresponds to strongly heterogeneous management approaches among regions (very high level of exploitation in the Landes forest, emphasis on nature conservation in the Alps, very limited exploitation in the Mediterranean area, etc.). This scenario aims to maintain the current overall felling rates, as recorded by the National Forest Inventory using field surveys (period of observation 2005-2013). We therefore use the harvest rates already integrated in MARGOT from historical data. As used in various previous studies (Colin and Thivolle-Cazat, 2016; Colin, 2014), this empirical strategy is robust in the short term (20 year horizon), but cannot take into account management changes related to the unbalanced structure of French forests (relatively young at present). This, therefore, forms a reference scenario, which is useful for comparing the levels reached by the two other prospective scenarios.

Box 4.1. The MARGOT forest resource model, projecting forest resources and future availability at the territorial scale

Principles and functioning of the model

The MARGOT model is used by IGN in many studies to project forest resources, future wood availability and carbon balances under different forest development scenarios (Colin *et al.*, 2017).

It is a demographic model that simulates changes in the forest characteristics of an area (from a region to the country) according to tree growth, natural mortality and timber harvesting. One of the essential features of the model is that it is based exclusively on data collected by the National Forest Inventory (IFN) statistical survey to describe the initial state of the resource and the natural dynamics of the forests of the areas concerned. Silvicultural scenarios can also be defined using NFI data, or defined externally together with professionals from the forestry & wood sector. The MARGOT model includes two demographic models for dealing with silvicultural diversity: the model of resource dynamics by age class, implemented in cultivated poplar plantations, and the model of resource dynamics by diameter class (Wernsdörfer *et al.*, 2012), implemented for all other forests. The model divides the 15.9 million hectares of forest available for wood production in France into 116 classes plus 2 classes for poplar plantations, each of which is subject to projection governed by specific assumptions. Each class groups together stands that are comparable in terms of species, land ownership, environmental conditions and silviculture practices. Thus, all stands in a given class, even though they are not spatially adjacent, may be subject to the same biological growth, mortality and harvesting assumptions under given development conditions (age or diameter class).

Due to the general nature of the modelling approach used in Margot, and the systematic and national nature of the IFN survey, forecasts take into account all forest types (species composition, soils, climates) and management practices that are found at the national level, as opposed to specific models, which can only be used for a given situation and, more often than not, only for a single species.

Implementation of management scenarios

The areas of expansion (including plantations) in the three scenarios (+ 40,000 ha/year) were added progressively to the simulation in the class corresponding to the regions, property types and species where forest expansion is currently the highest. The harvest rates for the 'Territorial dynamics' scenario were determined from observations of harvesting made directly on the IFN plots. This approach makes it possible to implicitly consider all factors that currently play a role in wood utilisation (operational difficulties, regional policies, owners' motivations, etc.). Harvesting rates in the 'Extensification' scenario are derived from the trends seen in the results of the FFSM sector model simulations (Chapter 5 and Box 5.1), and therefore reflect the underlying economic assumptions. Finally, harvest rates in the 'Intensification' scenario were defined on the basis of the harvest rates observed by IFN and applied to the 'Territorial dynamics' scenario, and then adjusted according to the previously defined levels of intensification in order to reach the objective of a 70 to 75 % increase at the national level by 2035. These adjustments were made 'according to expert opinion', according to the capacity of the different resource compartments to allow additional harvesting in keeping with the rationale of this scenario. This analysis was carried out by major ecological region, type of property, species and size category of wood. This intensification was applied progressively from 2015 to 2035, after which the 'intensive' harvest rates were kept constant until 2050. The integration of the reforestation plan into the 'Intensification' scenario was carried out in two stages:

– simulation of clear cutting in existing stands located in areas to be reforested by 2030, as identified by the experts who prepared the reforestation plan;
– simulation of growth and harvesting in reforested areas according to the assumptions defined by the 'reforestation plan' group.

Limitations of the model for long-term projections of the carbon balance

Given that forestry cycles in France are marked by slow and progressive changes, this type of statistical model based on field data is particularly robust in short- and medium-term projections. For longer-term projections, however, the stationarity of growth parameters and, to a lesser extent, mortality, makes it difficult to use the MARGOT model in isolation. Indeed, environmental conditions are changing with climate change, and the gradual densification of stands, particularly as a result of silviculture, tends to change growth rates. However, it is precisely these simultaneous variations in climate and management practices that we wish to explore in this study, and the 2050 horizon is clearly too distant to assume that transition matrices will remain constant. Taking these long-term modifications into account requires research and development, and an initial thesis is currently being undertaken at IGN to model the relationships between growth, population densification and climate change within the MARGOT model.

With this in mind, in order to respond to the particular challenges of the study, methods have been devised to take into account, in a schematic manner, the impacts of climate change[16], severe disturbances, and the effects of density dependence. On this last point, the IGN created an experimental version of MARGOT in which the growth parameter (transition between diameter classes) was made dependent on the relative density of the stands, in order to comply with the production-saturation law at the stand scale.

The 'Intensification' management scenario aims at increasing harvesting, on the assumption that a number of current bottlenecks will be removed, e.g. development of the exploitation and utilisation of hardwoods, increased harvesting of large softwoods, increased harvesting in the Mediterranean and mountain regions, etc. The objective is a gradual increase in the level of harvesting, to reach an increase of between 70 and 75% by 2050. Since we are unable to use economic modelling to determine the impact of harvesting as inputs for the MARGOT model[17], the harvesting rates used here consist of an 'expert review' of current rates in order to increase them in line with the known behaviour of stakeholders, with the possibility of additional harvesting depending on the type of forest. Intensification was determined by compartment by combining property type, region, species and diameter class, and was mainly aimed at increasing harvesting from private and communal forests, from hardwoods, and from large softwoods. The reforestation plan specific to this scenario was implemented in the resource model. It was deliberately simulated until 2100, partly in order to ascertain the long-term consequences of the chosen planting regimes, but also to identify the huge influx of wood to the market that will occur a few decades after the short replanting period (2021-2030).

The 'Extensification' scenario is something of a special case. It aims to maintain the overall harvest volumes in m^3/year over the entire period, unlike the 'Territorial dynamics' scenario, which involves freezing the *rates* of harvest at their current level. The temporal change in harvest rates in the 'Extensification' scenario is a direct result of the simulation results of the FFSM sector model, and therefore of the underlying economic assumptions (such as the reduction in the managed surface area). These behaviours according to regions and species were made compatible with the 116 classes in the MARGOT model, and then used to calculate harvest rates for the MARGOT 'Territorial Dynamics' scenario. For the first simulation period, this equates to the current harvest volumes. This method permitted the retention of regional trends and the temporal evolution of harvest rates as simulated by the FFSM model, while remaining consistent with the current harvest volume and its distribution as observed by IGN in 2015.

As shown in Figure 3.4, the harvest levels resulting from this approach will clearly rise with the intensification of forest management. The 'Extensification' scenario would by 2050 lead to levels very similar to those of today in the hardwood sector, and even slightly lower than those of today for softwoods. They increase by nearly 40% and 20% for hardwoods and softwoods, respectively, in the 'Territorial dynamics' scenario. The difference is even more pronounced when moving to the 'Intensification' scenario: harvest increases would be around 70% for hardwoods and over 50% for softwoods compared to the initial period (2016-2020).

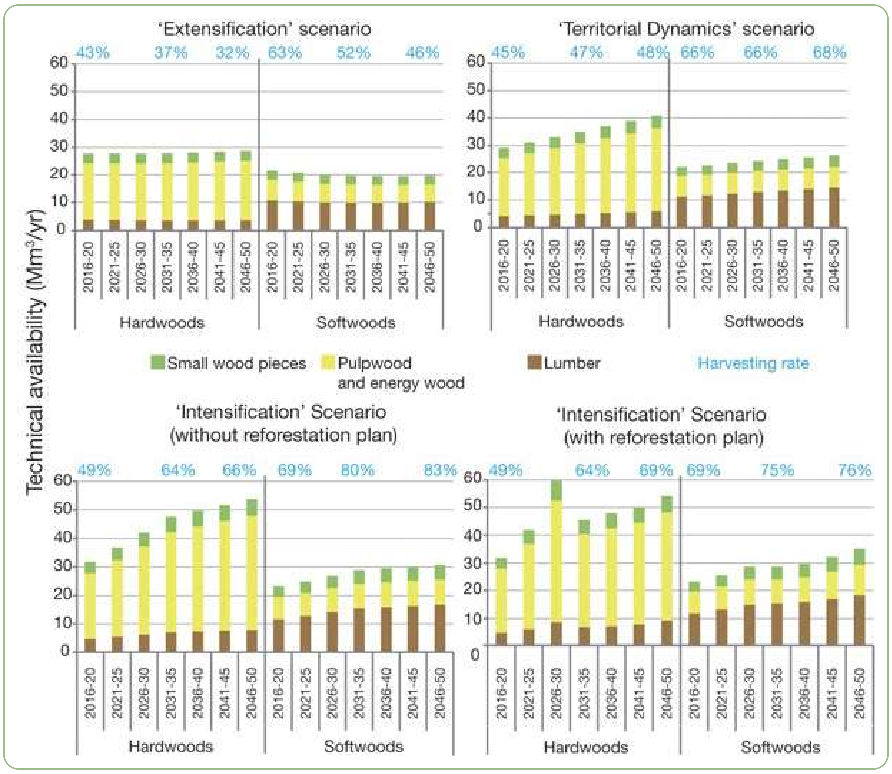

Figure 4.1. Changes in technical availability by type of wood use and changes in the rate of extraction (as a % of net growth) according to the management scenario.

Standing timber stocks, harvests, and carbon storage in the forest ecosystem

A standing stock with variable growth according to the scenarios

The simulated scenarios extend the trend of wood accumulation observed since the establishment of the IFN in 1958, though to a greater or lesser extent depending on the management scenario. The 'Extensification' scenario leads, as expected, to very high accumulation, with the standing volume reaching 4.5 billion cubic metres of strong stem wood by 2050 (3 billion for hardwoods + 1.5 billion for softwoods), compared to 2.8 billion cubic metres in 2016 (Figures 4.2 and 4.3). The 'Intensification' scenario provides for greater harvesting, particularly in large woodlots, and by the introduction of a reforestation plan that consists of firstly cutting down the stands to be reforested. Despite the very active nature of these harvesting practices, the standing stock will continue to increase to 3.6 billion cubic metres of strong stem wood by 2050, underscoring the strength and inertia of the current accumulation trend. These upward trends also reflect the sustainability of the simulated harvests in all three scenarios.

The increase in stock is mainly due to hardwoods and private forests. Across the three management scenarios, the volume of large and very large logs continues to increase sharply, including in the 'Intensification' scenario where harvesting effort is nevertheless concentrated on them. In terms of stocks and availability, the implementation of a progressive reforestation plan of 500,000 ha spread over ten years results in a short-term peak harvest during the decade of clear cutting and reforestation, while the additional availability linked to the new plantations arrives gradually, and is evident only after 2050.

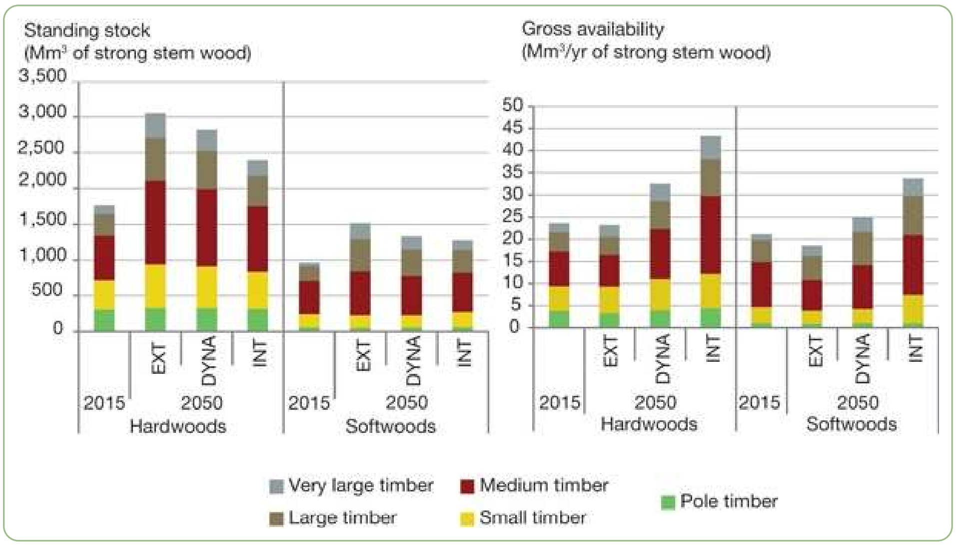

Figure 4.2. Distribution of standing stock and availability by diameter category and by management scenario in 2015 and 2050 (in Mm³/year, volume of strong stem wood).

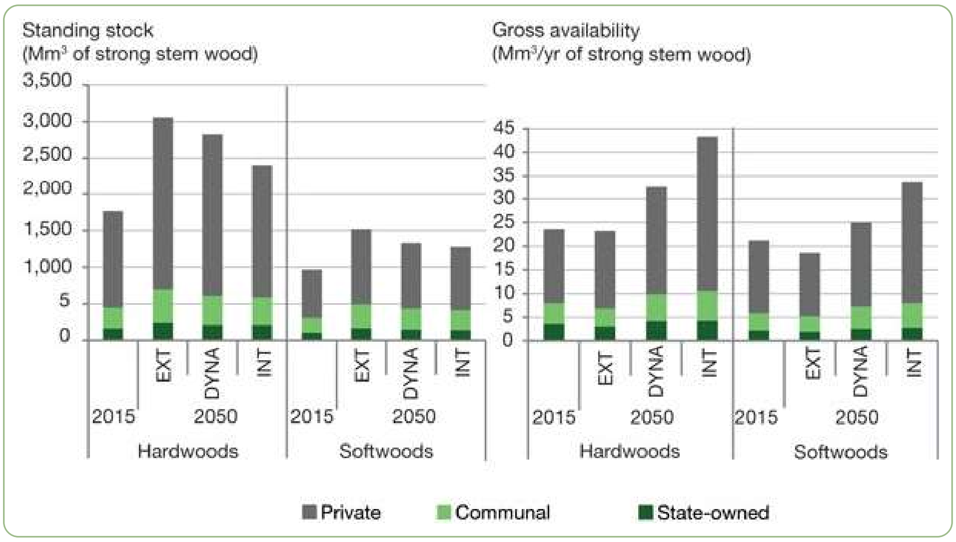

Figure 4.3. Distribution of growing stock and availability by property type under each management scenario in 2015 and 2050 (in Mm³/year, volume of strong stem wood).

In this context, with forest management changes at this stage the sole factor of interest (and not the effects of climate change over the study period), biological production of hardwoods would follow an upward trend due to the relative youth of the stands: from 90 million cubic metres per year (total aerial volume), it would increase to 110 to 130 million cubic metres per year in 2050 depending on the management scenario. Linked to the entry into production of new, large areas, this increase leads to an acceleration of the accumulation phenomenon, regardless of the management method used. These results suggest that, firstly, there is scope for a dynamic forest policy given the current accumulation dynamics, and secondly, this would be compatible with the maintenance of significant stocks of large timber (with associated biodiversity).

Variation in forest carbon storage between the different scenarios

On these bases, the annual storage in the ecosystem (biomass, dead wood and soil), which at the beginning of the period (2016)[18] is close to 85 $MtCO_2eq$/year, could diverge significantly between the three management scenarios (Figure 4.4). Steadily increasing to 132 $MtCO_2eq$/year at the end of the period (2046-2050) in the case of the ‘Extensification’ scenario, it could increase more slowly in the ‘Territorial Dynamics’ scenario (96 $MtCO_2eq$/year) and decrease slightly in the ‘Intensification’ scenario, whether or not it is implemented with a reforestation programme (approximately 62 $MtCO_2eq$/year).

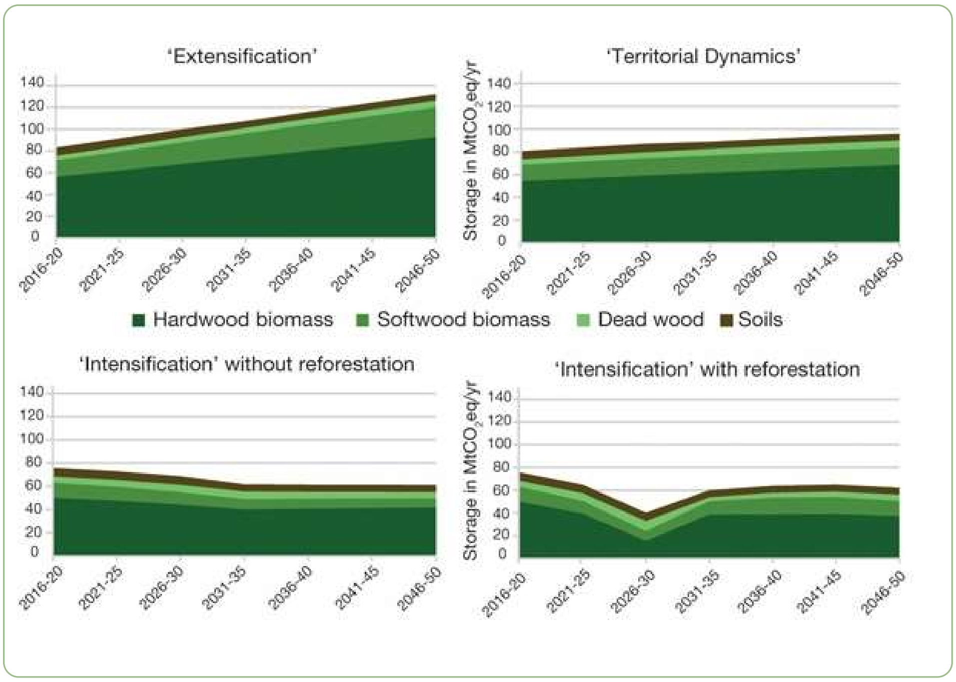

Figure 4.4. Changes in annual carbon storage in the French forest ecosystem over the period 2016-2050, according to the three management scenarios (in $MtCO_2eq$/year).

In the latter scenario, when the reforestation plan is included, the loss induced by the concentration of clear-cutting between 2021 and 2030 is quickly compensated for in the following decades. However, the 2050 horizon is too soon for the benefits of these new plantations to emerge in terms of annual carbon storage. As discussed in Chapter 3, these benefits would only really become apparent after 2050 and would peak around 2070. The low gain of these plantations is also linked to the criteria used to develop the reforestation plan. By imposing a strong accessibility constraint and focusing on stands at a silvicultural impasse (Annex), this plan would not necessarily concern the least productive areas, and would make the objective of +10 m^3/ha/year difficult to achieve. The expected gains from this plan would therefore be lower than those hoped for in the goals of this scenario (Chapter 3).

Sensitivity of results to assumptions regarding growth processes in forest stands

These carbon storage dynamics show that the French forest is not in a state of equilibrium, but rather is following a trend of increasing standing stock. However, with currently-available tools, which are robust for closer projection horizons (2030-2035) but which have potential limitations for more distant projections, this continuous growth trend would not appear very compatible with the ageing of forest stands. Indeed, if growth dynamics of standing stocks remain unchanged, the projection of the average stock per hectare would reach somewhat unrealistic levels by 2050, particularly in the case of the ‘Extensification’ scenario (average of 270 m^3/ha, nationally, compared with 170 m^3/ha at present). This simulated average stock level in 2050 would be much higher than that of State-owned forests (190 m^3/ha), which has been generally stable since 1980 and is considered characteristic of forests managed in metropolitan France.

This finding led us to seek a more effective way of addressing competition within the forest stand, which would tend to increase as the stand becomes denser. Indeed, one of the long-term limitations of the MARGOT model is that the calibration of dynamic parameters (growth, mortality, etc.) is based on observational data associated with the current context. However, should this setting change over time (significant increase in standing volume, changes in environmental factors, changes in silvicultural practices, etc.), the dynamic parameters should also change. This phenomenon is currently neither modelled nor simulated. The density-dependent version of the Margot model, which is the subject of IGN research, was consequently tested here, making growth parameters (the rate of transition of a stem from one diameter class to the next) and recruitment dependent on the relative density of the stands, thus complying with the law of saturation of production at the stand level.

The introduction of density-dependent growth into the simulations is analogous to a sensitivity analysis of the previous results. This significantly modifies the trends in the sequestration capacity of French forests (see Figure 4.5). Without changing the ranking of the scenarios, the gap between them narrows considerably. The ‘Extensification’ scenario would result in an increase in the annual storage rate by 25% (compared to 60% previously) between 2016 and 2050, the storage rate would remain stable under the ‘Territorial Dynamics’ scenario and its fall would be slightly more pronounced under the ‘Intensification’ scenario.

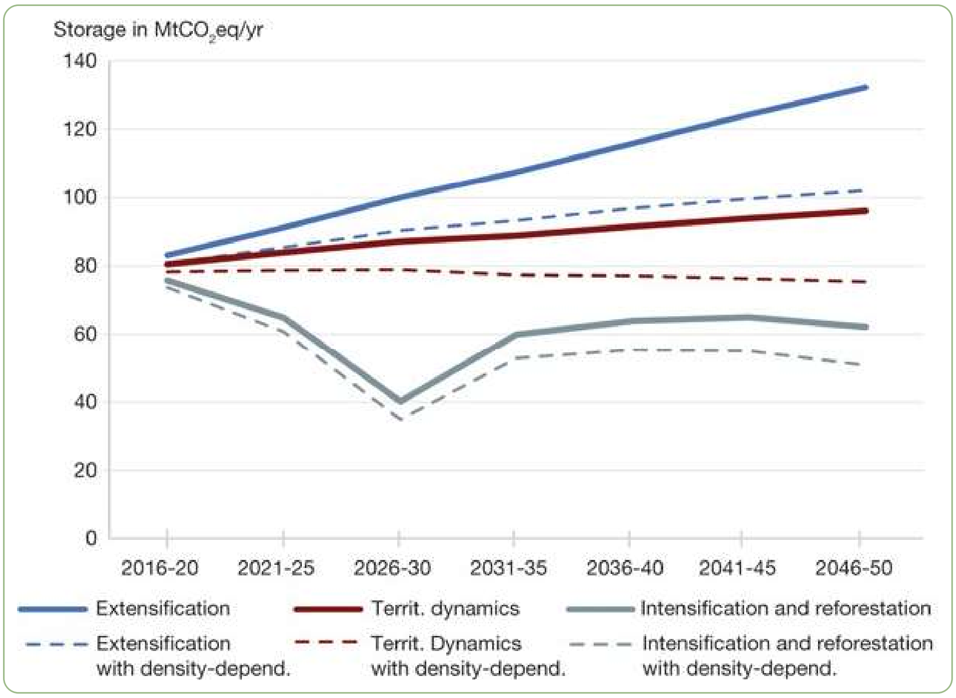

Figure 4.5. Annual carbon storage in forest ecosystems over the period 2016-2050 and according to the three management scenarios, and a trial of density dependence (dd) in the Margot model. (in $MtCO_2eq$/year).

Finally, the difference in the annual rate of carbon sequestration in French forest ecosystems without considering density dependence would in 2046-2050 be 36 $MtCO_2eq$/year between the ‘Extensification’ and ‘Territorial dynamics’ scenarios. However, this would be reduced to 27 $MtCO_2eq$/year if this phenomenon were considered. This gap would also be reduced between the ‘Extensification’ and ‘Intensification’ scenarios, falling from 70 $MtCO_2eq$/yr to just over 50 $MtCO_2eq$/yr in favour of the ‘Extensification’ scenario in 2050, if the effects of the densification was modelled.

The low level of carbon storage in wood products

The volume of wood that can be exploited by the sector is estimated as the difference between the total above-ground volume removed and the small wood pieces, stumps, bark, etc., left on site. This exploitable volume has been separated into three broad applications: lumber, pulpwood and energy wood. The distinction of volumes between lumber uses on the one hand and industrial and energy wood uses on the other is based on the percentages set in the FFSM economic model using national wood harvesting statistics and use by primary processing industries. These rates have been applied to net volumes of operational losses, which represent 8% of lumber volume, 15% of pulpwood and energy wood volume and 50% of the volume of small wood pieces.

As discussed previously, the scenarios are strongly differentiated by their respective volumes of wood that enter the sector. In the current climate, they would remain almost constant at approximately 40 Mm^3/year for the ‘Extensification’ scenario, rise to nearly 60 Mm^3/year in the 'Territorial dynamics' scenario and exceed 70 Mm^3/year in the 'Intensification' scenario (Figure 4.6). Nevertheless, and contrary to the rationale behind certain management scenarios, the breakdown between types of use (timber, pulpwood and energy wood) could not be differentiated by trajectory: regardless of the management scenario, approximately 38% remains used for energy wood, 28% for pulpwood, and 34% for timber.

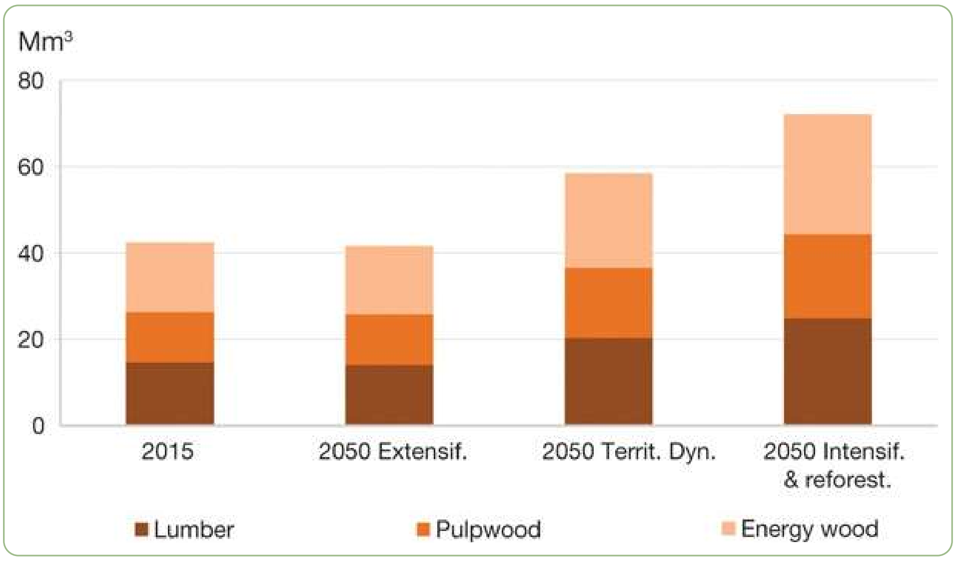

Figure 4.6. Breakdown of wood volumes entering the sector in 2015 and 2050 according to uses (lumber, pulpwood and energy wood) and the three management scenarios (in Mm^3).

Thus, harvest increases by 2050 will be only slightly constrained by the status of the resource, either in absolute terms or in terms of its breakdown by use. In fact, the uses of wood (and not its potential quality) depend very strongly on demand from the sector. The latter would benefit from a more explicit economic modelling, which could result from optimal calculations that match supply and demand[19].

Only timber and industrial wood are stored in wood products, and this should take into account the annual end-of-life losses of previously accumulated wood products. It should be recalled that stocks at the beginning of the study period were estimated at 300 $MtCO_2eq$ for lumber and 80 $MtCO_2eq$ for industrial wood, to which half-lives of, respectively, 20 and 5 years were applied (Chapter 2).

Under these assumptions, overall annual storage in products will remain low, following a progression in line with the harvest rates targeted by each of the scenarios. At virtually zero under 'Extensification' (where the absolute harvest level remains close to its current value), it approaches 3 to 6 $MtCO_2eq$/year in the other two scenarios (Figure 4.7). The peak recorded for the 'Intensification' scenario represents the value, mainly in the form of pulpwood, of the harvesting of stands planted under the reforestation plan. This level remains very low compared to storage in the ecosystem.

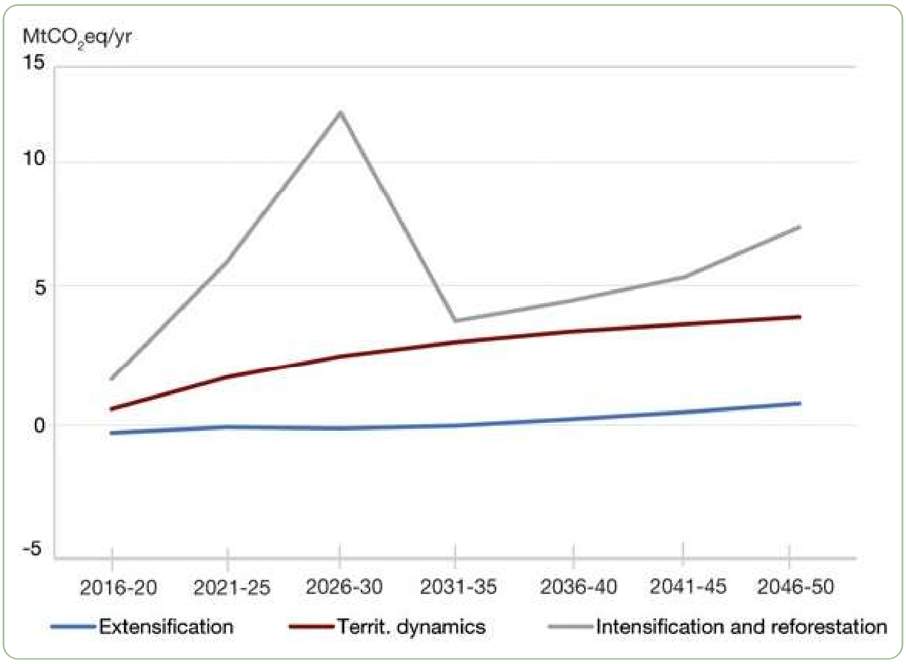

Figure 4.7. Annual carbon storage in products from the French timber sector according to the three management scenarios (in $MtCO_2eq$/year).

The variability of these results between the scenarios appears to be low. This is no doubt due, in part, to the assumptions used, the limitations of which have been examined earlier (Chapter 1). These include half-lives, processing efficiencies, breakdown by product, end-of-life fate and recycling, as well as changes in these assumptions over time. To improve the estimates, a combined modification of these would be necessary, such as stimulating demand and structuring supply to increase the share of lumber, changing product types towards longer-life products, improving technologies that increase efficiencies etc. This merits testing, for example, with the CAT tool for the detailed representation of carbon flows in the timber sector developed by INRAE in Nancy and AgroParisTech (Pichancourt *et al.*, 2018). As mentioned in relation to density dependence, it is a question of making explicit the dependence of storage dynamics on usage changes in the sector.

The magnitude of emissions avoided through substitution, and the associated uncertainties

Given the low contribution of storage in wood products to the carbon balance, it falls mainly on substitution effects to form the basis for the wood sector's contribution to this balance. Assuming that the substitution coefficients used for the current carbon balance, as presented in Chapter 3, remain constant over time, the level of avoided emissions linked to the substitution of high-emitting products is significant, especially as harvest levels intensify. It remains constant at around 36 $MtCO_2eq$/year under the 'Extensification' scenario, whereas it increases steadily to 50 $MtCO_2eq$/year under the 'Territorial dynamics' scenario (Figure 4.8).

With the implementation of the reforestation plan, the level of avoided emissions is more variable over time in the 'Intensification' scenario. In this case, it would peak at approximately 65 $MtCO_2eq$/year for the period 2026-2030, which corresponds to the processing (mainly as pulpwood) of wood harvested during clear-cutting prior to reforestation. It would then increase steadily from 52 to 66 $MtCO_2eq$/year from the period 2031-2035 to 2046-2050.

The contrast between the simulations with and without a reforestation plan highlights the impact of reforestation on avoided emissions. Indeed, without a reforestation plan, the increase in avoided emissions would follow the increase in harvest rates until 2035, and then becomes much slower due to the stability of harvest rates. On the other hand, the reforestation plan, with plantations starting to come into production at the end of the period studied, would result in a 25% increase in avoided emissions between 2030 and 2050, an increase mainly due to substitution by lumber and pulpwood.

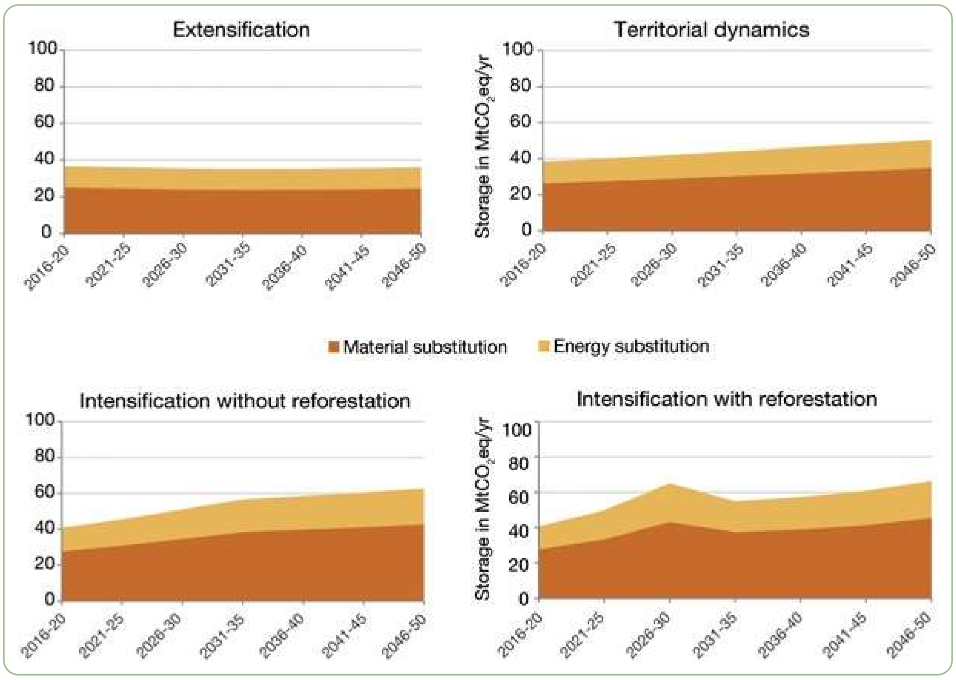

Figure 4.8. Trends in CO_2 emissions avoided as a result of substitution by wood products over the period 2016-2050, according to the three management scenarios (in $MtCO_2eq/an$).

Logically, given the substitution coefficients assigned to lumber and pulpwood on the one hand and to energy wood on the other, as well as the share of energy wood in the volumes entering the sector, the substitution effects are mainly due to lumber and pulpwood.

Over the entire 2016-2050 period, the cumulative avoided emissions range from 1,250 to 2,000 $MtCO_2eq$, depending on the scenario (Figure 4.9). The 60% difference between the 'Extensification' and 'Intensification' scenarios is, as expected, likely to compensate for all or part of the forest storage differential (highlighted above) between the two scenarios.

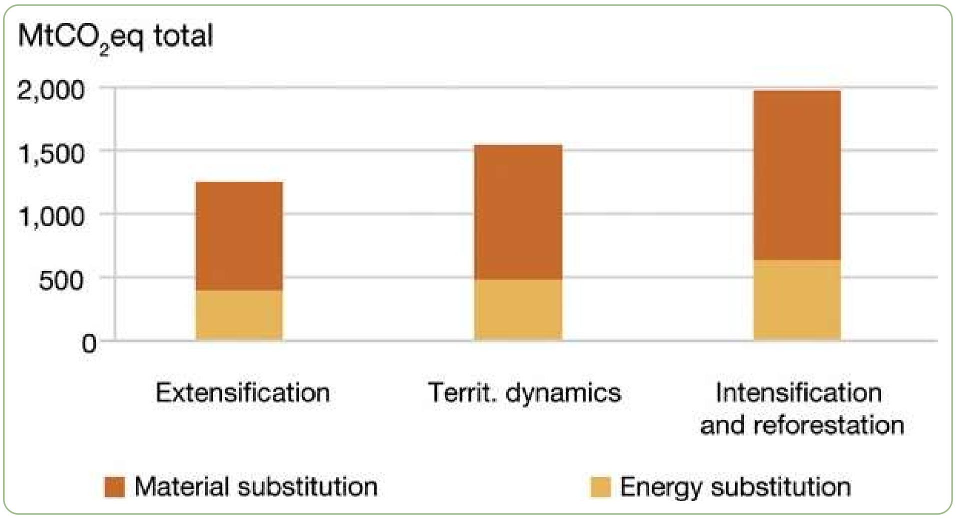

Figure 4.9. Cumulative CO_2 emissions avoided by substitution effects over the 2016-2050 period under the three management scenarios (in $MtCO_2eq$).

The level of emissions avoided is nevertheless highly dependent on the substitution coefficients used and on the breakdown between wood uses. These coefficients are also assumed to be stable over time. The coefficient for wood energy is 0.5 tCO_2/m^3 with a current range of variation (from the literature) of 0.37 to 0.64, while finished products made from pulpwood and lumber are both assigned 1.6 tCO_2/m^3, with a very wide current range of variation of 0.59 to 3.47.

It is obvious that the overall level of substitution effects, as assessed here, is extremely sensitive to the values of the substitution coefficients used, particularly for wood used as a material, given that we have adopted a single coefficient value for all types of lumber and pulpwood use. Taken as a whole, our coefficients are slightly higher than those used by Rüter *et al.* (2016), but they are still far from the extreme values we have found in the literature. Differences in substitution effects between management scenarios would have been more marked had we been able to reflect the increase in lumber usage in line with the rationale of the 'Intensification' scenario, and had we considered a variation in substitution coefficients that were more favourable to lumber.

A better representation of the pattern of use (lumber, pulpwood and energy wood) and its variation by scenario would be appropriate here. Wood categories (species and size) processed by the various industries have undergone strong changes and fluctuations over the last ten years. For example, in Germany, the ratio between energy and lumber uses for beech wood has very quickly shifted in favour of energy. In contrast, new processes for the production of reconstituted wood make it possible to convert small diameter logs into lumber that would otherwise have been used as pulpwood.

The maintenance of constant substitution coefficient values for lumber, pulpwood and energy wood over the 2016-2050 period raises questions, as it is particularly difficult to determine whether substitution coefficients will increase or decrease without the use of technological knowledge that can rigorously analyse the way(s) in which competing technologies could evolve between now and 2050. Such a prospective analysis should simultaneously predict the development of production technologies for the different wood products and their alternatives, the emergence of new uses, and substitutes for current products that are high emitters of greenhouse gases. Obviously, the complexity of making such estimates, along with the assumptions they require, will heighten their fragility. Predictive research reaches its limits when it is based on quantitative information which, when projected into the future, creates new uncertainties that are much harder to resolve than those related to biogeophysical mechanisms.

While Rüter *et al*. (2016) estimate a 20% reduction in material coefficients between 2010 and 2030, certain technological options, or the scarcity of primary resources required for certain alternative products (sand for concrete production, for example), could lead to this assumption being tempered or even reversed. In addition, our scenarios for intensifying wood use are designed around an increasing use of hardwood in construction, which is likely to specifically benefit the French forestry & wood sector. The density of hardwood is approximately 20% higher than that of softwood, as is the substitution coefficient expressed in $tC0_2/m^3$. Consequently, even if a decrease in the wood-material substitution coefficients would naturally be expected, an increase for all or some of the wood materials cannot be ruled out. Therefore, it is difficult to choose one option over another.

In view of these points of debate, as well as the levels and nature of the uncertainties, we adopted a single coefficient for lumber and pulpwood (the midpoint of the Sathre and O'Connor range) and set it to remain constant over time. We feel that, before modifying these coefficients, it would be necessary to explain how these substitution effects, given their importance in the sector's contribution to climate change mitigation, are linked to the production technologies and those of competing industries, all of which can evolve over time in different ways depending to the rationale of the scenarios.

Carbon budgets are largely positive, but sensitive to the assumptions and parameters used.

Although risky, given the uncertainties regarding the substitution coefficients, the effects of stand ageing and densification, and the lack of contrast in uses between scenarios, the three carbon budgets obtained for the simulated period (2016-2050) by combining the various components analysed above are presented in Figure 4.10 for both the standard and density-dependent versions of MARGOT.

The major contribution of this sector to climate change mitigation

The total carbon balance of the French forestry & wood sector will vary between 120 and 170 $MtCO_2eq$/year by 2050 (Figure 4.10), which is very significant when compared to total national emissions, which are currently approximately 350 $MtCO_2eq$/year (see Citepa, 2017).

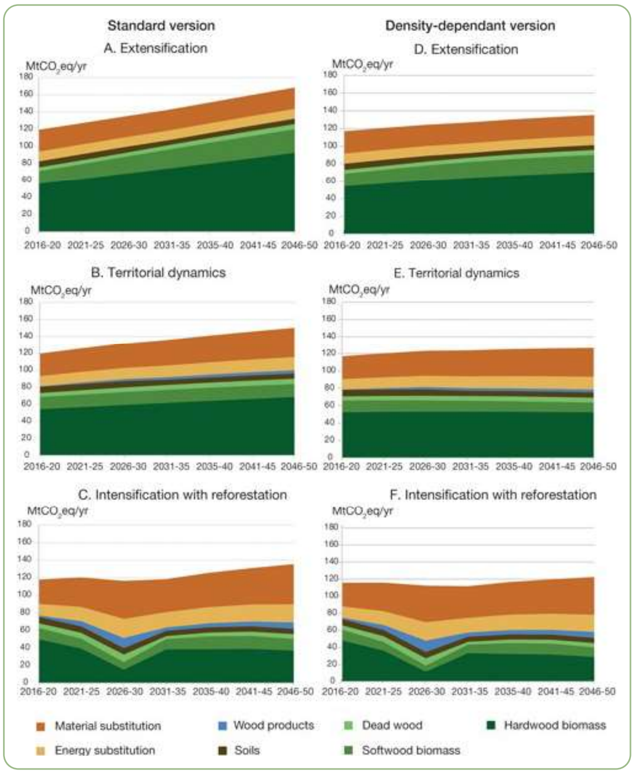

Figure 4.10. The carbon balance of the forestry & wood sector for the three forest management scenarios with the current version of the MARGOT model (A, B, C) and the density-dependent variant (D, E, F) (in MtCO$_2$eq/year)

Two general results are clear:

– on the one hand, irrespective of the scenario and forest growth hypothesis, the carbon balance remains positive, reflecting the favourable impact of French metropolitan forests on greenhouse gas emissions up to 2050, even under a wide range of assumptions;

– on the other hand, the carbon balance is increasing or stationary over the entire period. It is essential to note that the latter result is by no means an intrinsic property of the forest ecosystem, but stems from two historically-dependent characteristics of the French forest resource: Firstly, the forests of metropolitan France are mostly young, resulting from the forest transition that began around 1830 and continues today (Denardou et al., 2018). Secondly, the abandonment of wood as a central economic commodity (Dangerman and Schellnhuber, 2013), which has enabled the regeneration of forests, led to the massive use of materials and processes that emit more greenhouse gases (fossil fuels, concrete, steel, aluminium, etc.). This, in turn, confers a unique environmental benefit on the use of wood (through substitution).

This historical dimension of the forest carbon sink has two important methodological consequences:

– Beyond the current forest expansion and storage phase, there is no reason why carbon exchanges between forests and the atmosphere should continue to result in a strong forest sink, as the gradual ageing of trees, increasing harvests, climatic constraints and recurrent forest damage could reduce or even reverse it;

– Current forest product use and at least some future uses can be credited with substitution effects, as their existence is the result of a trade-off between materials and processes, and if the trade-off had been more to the benefit of the forest stock, the surplus storage would be counted as a climate benefit.

A trade-off between carbon storage in forests and substitution effects

At this stage of the analysis, the comparison between the three management scenarios indicates that the low harvest and use scenarios provide an advantage in terms of carbon balance (Figure 4.11). However, there is also a marked contrast in terms of the relative weight of standing stock on the one hand, and substitution effects on the other:

– Under the ‘Extensification’ scenario, the near-constant harvest level over time results, on the one hand, in no change to wood supply in the sector, nor in the expected benefits of substitution. On the other hand, there is a rapid increase in the standing stock of softwoods, and especially hardwoods. The proportion the total

carbon balance accounted for by storage in biomass thus increases sharply over the thirty-four years under consideration, while that linked to substitution effects declines accordingly;
– Under the 'Territorial dynamics' scenario, the different components of the carbon balance maintain roughly the same proportions over time. The higher harvest levels than in the previous scenario result in a slowdown of storage in the forest and an increase in substitution effects, the latter however being slightly faster than the former;
– Under the 'Intensification' scenario, the large amount of clear-cutting prior to 2030 leads to a temporary drop in biomass storage, but this is partly offset by the stocks of wood products and the substitution effects that their use creates. The overall carbon balance remains approximately stationary until 2035, before rising slightly thereafter.

In all three scenarios, as in the current situation, hardwood forest storage dominates the carbon balance, followed by the material substitution effect, and finally softwood forest storage. The other components of the balance, notably storage in wood products or dead wood, continue to play a minor role and act as stabilisers due to transfers between components.

At this stage of the analysis, the three management scenarios differ in terms of their total carbon balance and the way in which it is distributed between storage in the ecosystem (unstable), storage in wood products, and avoided emissions (both associated with the economic sphere and generally long-term). By 2050, 71% of the 'Extensification' scenario's carbon balance would be concentrated in the ecosystem, compared with 65% in the economic sphere for the 'Intensification' scenario. In other words, the decrease in storage speed observed in the 'Intensification' scenario, whether seen as a trend over the entire period or, more specifically, at around 2030 (with harvesting across large areas), is partly offset by the other components of the system, in this case mainly the stock of wood products and substitution effects.

Therefore, the policy choice between the management options is not only based on the total carbon balance of each scenario, but also on the way in which each overall balance is distributed between its components, and the potential for development of the bioeconomy and its longer-term effects.

More realistic forest growth assumptions reduce the differences between scenarios

With the current version of the MARGOT model (Figures 4.10A, 4.10B and 4.10C), we see virtually linear changes in the various components of the carbon balance. Only the strong disturbance induced by the harvests prior to the implementation of the reforestation plan disrupts this trend for a few years, with no other disruptions to the very linear trends seen in the other components. However, as noted previously, were the mechanisms for growth in forest biomass to be maintained until 2050 at the same level as at present, this would lead to unrealistic levels of wood stock per hectare, particularly for the 'Extensification' scenario. Thus, given the relative immaturity of French forest stands, there is probably a need to factor in a decline in their capacity for further carbon storage as stand densities increase over time.

The introduction of this so-called 'density-dependent' variant induces an alteration to carbon storage in forest biomass, which is more pronounced with lower harvests, since the densification of stands slows down individual tree growth (Figures 4.10D, 4.10E and 4.10F). This change is quite pronounced in the 'Extensification' scenario, with the growth rate of carbon storage in forest biomass slowing sharply. It results in a quasi-stabilisation of carbon storage in forest biomass in the case of the 'Territorial dynamics' scenario and in a slight slowing down of the recovery of carbon storage in biomass under 'Intensification'. Under the latter scenario, lower stand density stimulates individual tree growth, which allows relatively good productivity to be maintained at the stand level (Houllier, 1991).

This difference in the storage dynamics in the ecosystem leads to a major divergence between the two versions of the model: the standard version amplifies the differences over time, while the density-dependent variant reduces them. Thus, with the standard version, the 2050 values vary between 130 and 170 $MtCO_2eq$/year, i.e. differences of +13% between 'Extensification' and 'Territorial dynamics' and +42% between 'Extensification' and 'Intensification'. The carbon balances of the three management scenarios obtained with the density-dependent version vary little (± 10%) by 2050: the 'Extensification' scenario exceeds the 'Intensification' scenario by only 10% and the 'Territorial dynamics' scenario by 7%.

There is clearly a need for further research, both to clarify the role of competition between individuals in stand dynamics at more distant horizons and to introduce it permanently into dynamic models of forest resources, such as MARGOT.

Results are sensitive to substitution coefficient assumptions

As seen when determining the parameters and coefficients for establishing carbon balances for the forestry & wood sector, another uncertainty that can significantly alter predicted carbon balances lies in the wide range of substitution effect coefficients found in the literature (see Table 1.5). These vary from 0.37 to 0.64 tCO_2eq/m^3 (mid-point of 0.5 tCO_2eq/m^3) avoided for wood energy substitution, and from 0.59 to 3.47 tCO_2eq/m^3 (mid-point of 1.6 tCO_2eq/m^3) avoided for wood materials substitution. The variables underlying this range of values are known (the diversity and nature of the relevant wood products and their substitutes, the technologies used for both wood processing and the production of substitute products, and the renewable or non-renewable resources they use etc.). The current discussion concerning the values to be used for the coefficients to be adopted, given the characteristics of the French forestry & wood sector and its alternatives, is complicated by the difficulty in foreseeing changes in most of these uncertain dimensions over a 30-year horizon. Faced with these uncertainties, the choice was made to opt for the mid-points of each range of values (0.5 tCO_2eq/m^3 for wood energy and 1.6 tCO_2eq/m^3 for wood materials). It is now necessary to consider the likely effects of the variability of these coefficients on the carbon balances of the projected management scenarios up to 2050, given the importance of the substitution component in the total carbon balances.

Firstly, we should carefully examine our choice of value for wood-energy substitution. Indeed, other recent studies have used far lower values than ours (du Bus de Warnaffe and Angerand, 2020; CGDD, 2018), which can be as low as 0.3 tCO_2eq/m^3 (compared to 0.5 tCO_2eq/m^3). However, this substitution effect is of relatively low significance to overall carbon budgets and, importantly, this significance remains constant over time in most scenarios. Therefore, using a lower value for the wood-energy substitution coefficient (e.g. 0.3 tCO_2eq/m^3) would not change the ranking of the scenarios, and would only marginally alter the variations in the total carbon balance already observed. It should nevertheless be noted that, since the weighting of wood-energy substitution is slightly higher and slightly increasing under the 'Intensification' scenario, the gap by 2050 between the total carbon balance of this scenario and the balances of the other two scenarios would widen very slightly if the wood-energy substitution performances were lower than those used in our analyses.

The sensitivity of the results to the substitution coefficient for lumber and pulpwood is potentially greater, given the importance of this component to overall carbon budgets, its role in the differences between scenarios, and the range of possible coefficient variations. For this reason, a sensitivity analysis was conducted using a range of values from 1.0 à 2.2 tCO_2eq/m^3, corresponding to ± 0,6 tCO_2eq/m^3 around the 1,6 tCO_2eq/m^3 used in earlier calculations. This range is well within the variation noted by Sarthe and O'Connor (2010b).

Figure 4.11 presents the results of this sensitivity analysis by comparing the cumulative carbon budgets over 2016-2050 at different coefficient levels for the standard and density-dependent versions of MARGOT. As expected, any lowering of the substitution effects of wood materials would result in a less favourable cumulative carbon balance under any scenario. Conversely, any improvement in these substitution effects would increase the role of the forestry & wood sector in climate change mitigation. In other words, regardless of the management scenario considered, the development of wood uses centred on products with a high substitution coefficient will enhance the mitigation capacity of the entire French forestry & wood sector. This benefit is, logically, even more marked when the chosen management scenario is oriented towards an intensification of harvests. Thus, the gap between the carbon balances of the three management scenarios is significantly reduced as wood material substitution coefficients increase.

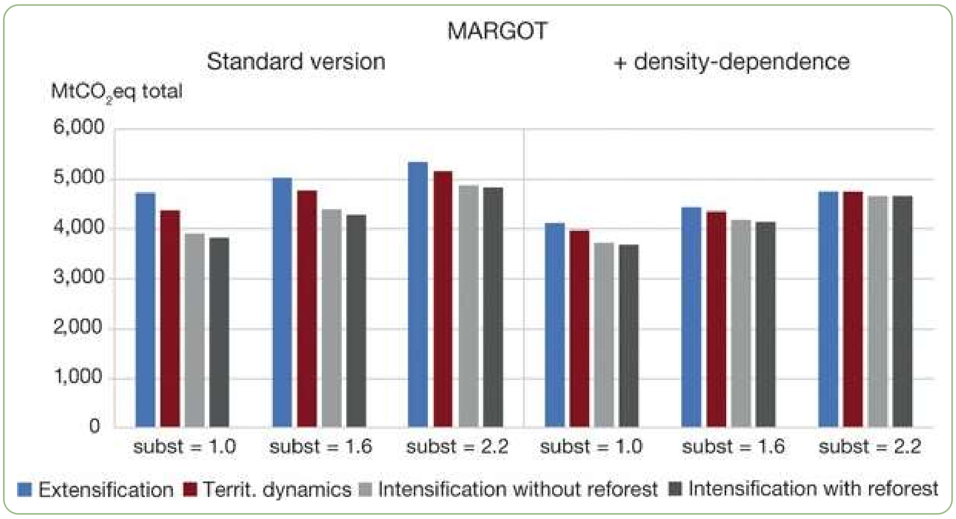

Figure 4.11. Cumulative carbon balance 2016-2050 under the different management scenarios, the standard and density-dependent versions of the MARGOT model, and the wood material substitution coefficient value (in $MtCO_2eq$).

When combined with the inclusion of the density dependence of forest biomass growth (which also mitigates the differences between scenarios), increases in substitution coefficients would even tend to negate the differences between the cumulative carbon balances of the three management scenarios considered here. The differential between the 'Extensification' scenario and the 'Territorial Dynamics' scenario would be, cumulatively over the entire 2016-2050 period, approximately 2% in favour of extensification under the density-dependent hypothesis, however this would completely disappear if the wood-material substitution coefficient were to be increased from 1.6 to 2.2 tCO_2eq/m^3 and would rise by approximately 4% in the opposite direction if this coefficient were to be reduced to 1.0 tCO_2eq/m^3. The difference between the 'Extensification' and 'Intensification' scenarios (in the order of 7% between the cumulative balances under wood-material substitution coefficients of 1.6 tCO_2eq/m^3, and assuming density dependence) would, with increased substitution coefficients, become negligible (1.5% with substitution coefficients of 2.2 tCO_2eq/m^3), but would increase significantly if this substitution effect were to decline (12% difference for substitution coefficients of 1.0 tCO_2eq/m^3).

At the conclusion of this analysis, it would seem that any conclusion giving a clear carbon balance advantage to the 'Extensification' scenario, in view of the gross simulation results performed here, would be somewhat premature. These gross results are extremely sensitive to the assumptions made in modelling forest growth processes and estimating the quantities of emissions avoided by substituting wood products (lumber and pulpwood) for alternative products that emit more greenhouse gases. Uncertainty related to forest growth may potentially be reduced through improved modelling based on further scientific knowledge. As has been seen, the inclusion of possible growth capacity limitations related to ageing forest stands significantly reduces the differences between scenarios. The future values of substitution coefficients are, for their part, more difficult to predict. Beyond the 'measurement errors' that are difficult to avoid here, these depend very strongly on the technological trajectories that the different relevant sectors will follow, on the changes that will occur in the use of wood products, and on the public policies that will guide or assist them in their transitional choices. Some of these changes may, as we have just seen, even cancel out any difference in the carbon balance between the three projected management scenarios.

Thus, the results are themselves sensitive not only to the properties of the chosen model, but also to the relevance of the assumptions and parameters used to assess the various components of the carbon balance and their changes over time. Further studies and more in-depth sensitivity analyses, could be conducted in order to study the effects, up until 2050, of climate change and forest management practices, as well as their interactions, on carbon sequestration in soils and in dead wood. More explicit representations of the behaviour of forest stakeholders and primary processors (through developments in FFSM-type economic models) or of carbon flows in the economic sphere (allocation of harvests to lumber/pulpwood/energy wood uses, different stages of processing, recycling, end-of-life disposal) would make it possible to build simulations of changes in the parameters related to wood products and their uses (substitution effect) over the simulation period.

Chapter 5
Economic barriers and levers for the implementation of forest management scenarios

The FFSM economic model (Box 5.1) provides an economic analysis of the envisaged management scenarios, and thus offers avenues for setting up public policy instruments that would need to be implemented in order to direct the dynamics of the sectors towards trajectories that they would not follow.

Box 5.1. Adaptation of the FFSM model to simulate the 'Extensification' and 'Intensification' scenarios.

FFSM (French Forest Sector Model, *modèle du secteur forestier français*) is a model that explicitly represents the French forestry & wood sector in as detailed a manner as possible. It is recursive (with an annual time step) and modular. It is built around a primary economic module describing timber markets, a second (called 'resource') representing forest dynamics, a third describing forest area management, and a final carbon accounting module (Caurla and Delacote, 2013; Caurla *et al.*, 2010). The strength of the model lies in the interconnection between these different modules.

The 'resource' module represents the national forest resource disaggregated according to three stratification criteria (regions, species, management types) and thirteen diameter classes. Parameters have been calibrated to make them identical to those used by Margot. It provides the 'market' module with the annual volumes available in the forest in order to determine the supply of wood products.

The market module (see Figure 2.3) is a partial equilibrium economic model. It represents the supply of three 'raw' products (hardwood lumber, softwood lumber, and pulpwood/fuelwood) and the demand for 6 processed products (sawn hardwood, sawn softwood, veneer, panels, pulp and wood for fuel) for each French administrative region. A 'raw product' is 'transformed' into a 'processed product' through a Leontief-type production function (i.e. with fixed input-output coefficients) that explicitly represents the transformation costs. The calculation of the economic equilibrium permits the establishment of a price, a quantity offered and a quantity consumed for each product and in each region. The model also calculates an optimal quantity of wood products traded, on the one hand, between French regions according to a transport cost gradient and, on the other hand, between each French region and the rest of the world.

The 'market' module transmits two essential pieces of information to the 'resources' and 'forest area management' modules. Firstly, it translates the supply calculated in terms of harvesting levels to the 'resources' module in order to integrate anthropogenic harvesting into the forest dynamics. On the other hand, the price it has calculated is sent to the 'forest area management' module, which represents forest managers in the form of a multi-agent model. Managers are modelled in the form of rational economic agents (i.e. profit maximisers) but are heterogeneous in terms of the level of 'active' management of their resource, their degree of risk aversion, and their expectations regarding climate change and future prices. According to their own characteristics, each representative agent uses the information at their disposal (product prices, climatic information) to allocate the forest areas made available by harvests to a specific management/species combination that is likely to maximise the expected income per hectare. When the surface area to be regenerated has been defined, the 'resources' module is then reintegrated.

Adaptation of FFSM's parameters to the sector's development scenarios

Among the very numerous parameters used as inputs to the FFSM, some have been modified to adapt them to the actors' behavioural changes envisaged by the two scenarios simulated in this chapter.

Similarly, the low degree of anticipation of managers in the 'Extensification' scenario is represented by anticipation parameters of the order of 0.2, both for future prices and for the climate, knowing that parameters close to zero represent a 'myopic' agent, i.e. one that makes its decisions for the future based solely on information from year t. Their risk aversion parameter is doubled compared to the current level. Conversely, forest managers are more 'enlightened' about climate and price changes (their anticipation parameters are close to 1, being set at 0.9) and their risk aversion parameter is very strongly reduced compared to the average value.

Limits of FFSM for this type of study

FFSM is a model more specifically designed for theoretical analysis. Although the model is, as far as possible, calibrated using real data, it integrates theoretical and stylised economic behaviour. In general, a model such as FFSM is used to highlight the broad magnitude and economic determinants of a phenomenon, as well as the sensitivity of a mechanism to the value of an economic parameter. Its scope is therefore clearly more analytical than predictive, contrary to some econometric models. This model is most often used to compare the relative values of economic output variables (price, quantities offered, demand, and surplus) under different scenarios, and to examine the nature and extent of the public policy instruments that would be necessary to orient the dynamics of the sectors towards trajectories that they would not otherwise follow 'spontaneously'. While an analogy can be made between economic models and atmospheric science models, a model such as FFSM could be likened to a climate model, while econometric models would be similar to meteorological models. A climate model does not have predictive value, but it can highlight the determinants of climate change and analyse its sensitivity to different parameters through the study of different alternative scenarios.

Beyond the simulation of the 'Extensification' scenario, the results of which were used to determine the harvests entered into MARGOT, an attempt was made to simulate the 'Intensification' scenario with FFSM. In order to contrast these two scenarios, some parameters of the model were firstly modified to adapt them to several of the central assumptions contained in the scenarios.

Assumptions for the simulation of the 'Extensification' and 'Intensification' scenarios

In terms of the stakeholder behaviour, the 'Extensification' scenario, as simulated by FFSM, is characterised by more passive forest managers (the proportion of their forest areas subject to 'active' management is considerably reduced compared to the present). They exhibit less foresight than at present regarding potential risks in terms of both climate and prices (their decisions are based solely on their current knowledge of production and market conditions, rather than anticipated future conditions). Wood supply does not depend on the forest stock, even if it increases (the elasticity of supply with respect to stock figures measured by the forest inventory is 0), so that an accumulation in the forest does not result in an increase in supply.

Conversely, the 'Intensification' scenario is characterised by more active managers than today (their management is based more on a profit maximisation rationale, and the proportion of forest areas subject to active management rises). Their risk aversion (climate and price) is lower than average and forest managers are more 'informed' than at present about the biological changes induced by climate change. Moreover, the supply of wood in this case is positively affected by changes in the forest stock; when the stock increases, supply increases, whereas when it decreases, the harvest is slowed down in order to maintain sufficient standing stock for future crops, in line with classical natural resource economics.

The implementation of these two scenarios in FFSM also differs on a central point, that of the incentives necessary for their application. While there is no policy to support the sector, nor any structural measures to support processing, transport or investment in the 'Extensification' scenario, the public policies introduced in an attempt to simulate the 'Intensification' scenario have taken two forms: firstly, direct subsidies for the consumption and production of wood products and, secondly, 'structural' measures aimed at reducing the costs of processing, transport and investment in forests. Finally, the reforestation plan of the 'Intensification' scenario is integrated by taking into account profit maximisation, thus favouring the most productive species. Thus, in the attempt to simulate the 'Intensification' scenario, these public policy instruments constitute adjustment variables. They are calibrated by 'controlling' three state variables: the additional volume to be produced by 2050 (approximately +45 Mm^3) on a national scale; the objective of not decapitalising (i.e. not harvesting more than the natural increase); and the area to be reforested (+ 50,000 ha/year from 2020 onwards).

Impediments to the growth of harvests as projected in the 'Intensification' scenario

Based on this set of assumptions, and by targeting the objectives defined for the 'Intensification' scenario, FFSM generated a series of harvest levels (Table 5.1), which are in fact closer to those generated by MARGOT for the 'Territorial Dynamics' scenario than to those generated for the 'Intensification' scenario. Except in the clearcutting phases related to the implementation of the reforestation plan (2021-2025 and 2026-2030), the annual harvest volumes are even slightly lower than those obtained in the 'Territorial Dynamics' scenario up to 2050.

The significant difference between the simulation results and the scenario objectives (a large increase in harvests) can be explained by certain characteristics of the FFSM model.

Firstly, the industrial structure of the sector as represented in FFSM cannot evolve over time, due to the absence of a module specifically dedicated to investments in the processing sectors. This hypothetical module would be of little relevance for near-term simulations, but of increasing value over longer time frames. In the current situation, the productive apparatus and its processing capacity remain the same, with no benefits from economies of scale.

Table 5.1. Variation (2016-2050) in annual harvests generated by FFSM for the 'Intensification' scenarios compared with the data used for the 'Territorial Dynamics' scenario (in Mm^3/year, total aerial volume).

	2016-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
'Intensification with reforestation plan' (FFSM results)	63.96	77.35	96.16	71.64	72.76	76.17	79.55
'Intensification without reforestation plan' (FFSM results)	63.96	69.84	70.18	73.96	74.9	77.89	80.20
'Territorial dynamics' (MARGOT data)	64.84	68.00	71.32	74.76	78.13	81.45	84.76

At the same time, and as is often the case in economic models, the price elasticities of supply and demand are assumed to be constant. In reality, these parameters can change significantly, either 'spontaneously', as appears to currently be the case (with the preference for wood products gradually becoming stronger), or as a result of the introduction of monetary or non-monetary incentives. For example, in the case of energy wood consumption, under a policy of subsidising the purchase of wood boilers, the demand function tends to become more rigid (demand becomes less elastic), and consumers find themselves in a 'technology lock-in' since, whatever the price of energy wood, they will continue to consume it because of the large investment in buying a boiler.

In the absence of these forms of flexibility in the industrial structure and behaviour in the model, the 'range of validity' of FFSM is limited to types of public support which do not modify the behaviour or structural characteristics of the sector. It is this which prevents the FFSM simulation from reaching the harvest objectives defined *a priori* for this scenario, instead limiting it to that used in the 'Territorial dynamics' scenario.

This result, which is technically constrained, nevertheless has an important empirical significance. Indeed, it highlights the current economic limitations of the French forestry & wood sector which, without major changes to its industrial structures and its production and processing capacities, and without a stimulation of consumer preferences for wood products, would find it difficult to spontaneously absorb the sharp increase in harvests envisaged in the 'Intensification' scenario.

The collective efforts required to increase production levels

It therefore seems economically difficult to achieve the harvest targets set in the 'Intensification' scenario without modifying the industrial structure and the behaviour of stakeholders. In the absence of these structural changes, and in order to work towards this objective, the FFSM model integrates support for the sector via a system of various types of incentives. However, even if the total incentives and support provided to the sector are increased to 6 billion euros by 2050 (Table 5.2), the expected harvest volume cannot, without structural change, exceed that of the 'Territorial dynamics' scenario, which maintains the current harvest rate.

Table 5.2: Public support and incentives introduced into FFSM in an effort to reach the 'Intensification with reforestation plan' scenario (current climatic conditions, risk-free, in millions of Euros)

	2015	2020	2030	2040	2050
Support for forest investment	0	23	24	27	30
Supply-based support	0	625	926	1,279	1,818
Transport support	0	5	10	10	17
Support for processing	0	434	941	990	1,634
Demand-based support	0	1,073	1,523	2,036	2,522
Total	0	2,159	3,424	4,343	6,021

To guide the sector towards this kind of increase in production volumes, FFSM therefore draws on several types of support and incentives aimed at the different parts of the sector (investment in forests, and support for supply, transport, processing and demand. Among these, direct consumer subsidies (i.e. subsidies which reduce purchase prices in the absence of a change in consumer preferences), which account for more than 40% of the total, would be the most costly incentives. Typically, however, such subsidies constitute a 'windfall effect' which explains a significant part of their cost. This introduces a subsidisation of consumption behaviour that would have taken place even if no subsidy had been introduced. In the case of a consumption subsidy, all consumption is subsidised, and not just 'additional' consumption. Processing assistance and supply-side incentives (i.e. those that support selling prices) represent the other important part of the support and incentives needed for the sector to absorb the additional production, representing 30% and 26% of the total, respectively. The former directly concern the industrial structures of the sector and can support changes to their production costs (without, however, leading to a reappraisal or overhaul of the organisation and functioning of the sector – given the nature of the model and of the assumptions. The latter are aimed at forest owners to encourage them to offer the standing timber available in the forest for sale.

Given the windfall effect induced by consumer subsidies and the model's rigidity with regard to consumer behaviour and investments in the sector, it is questionable whether achieving this market equilibrium would necessarily require such a level of support and assistance. In effect, this could be achieved, at least in part, simply by relying on consumption behaviour evolving towards wood products on its own, either through awareness of the need to mitigate climate change, or in response to investment support directed towards wood products. Strong stimulus and restructuring of the productive apparatus also appear necessary in order to increase the processing capacities of the sector and better orient production towards products with high added value and/or high mitigation potential. This would require a set of public or private incentives more strictly oriented towards investments in the sector than towards direct support to the market.

The activation of these instruments (which the tools used here do not fully integrate) will determine the real possibility of increasing the levels of wood harvesting in French forests, and thus approach the levels envisaged for the 'Intensification' or even 'Territorial dynamics' scenarios.

Trends in the supply-use balance up until 2050

Table 5.3 presents the changes in the quantities of wood products supplied, consumed, exported and imported by the French forestry & wood sector up to 2050 under the two scenarios 'Extensification' and 'Intensification with a reforestation plan' as simulated by the FFSM, and distinguishing between primary and processed products.

Table 5.3. Change (2015-2050) of the terms of the supply-use balance by primary and processed product for the 'Extensification' and 'Intensification' scenario as simulated by FFSM.

	Volume 2015 (Mm³)		'Extensification' scenario Δ 2015-50 (%)				FFSM 'Intens Δ 2015-50 (%	
	Prod[1]	Consu[2]	Prod[1]	Import[3]	Consu[2]	Export[3]	Prod[1]	Im
Hardwood lumber	6.3	5.1	+ 7.9		+ 2.0	+ 33.3	+ 50.8	
Softwood lumber	21.5	20.2	+ 0.0		− 0.5	+ 16.7	+ 26.5	
Pulpwood – Energy wood	46.6	44.4	+ 4.1		+2.0	+ 45.5	+ 53.2	
Hardwood sawn timber	2.3	2.4	0.0	0.0	+ 4.2		+ 34.8	0.0
Softwood sawn timber	10.7	13.3	− 0.9	− 4.0	− 1.5		+ 25.2	+4
Board	5.5	7,5	0.0	− 5.0	− 1.3		+ 38.2	+1
Veneer	0.5	0.8	0.0	0.0	0.0		+ 20.0	0.0
Pulp and paper	7.2	10.9	+ 4.2	− 2.8	+ 0.9		+ 48.6	0.0
Energy wood	25.5	25.6	+ 2.0	0.0	+ 1.6		+ 51.4	0.0

[1] For primary products, the quantity supplied corresponds to the quantity entering the sector upstream, regardless of its origin (forest or not) or its destination (domestic processing industries or exports). For processed products, the quantity supplied is the quantity leaving the domestic processing industries (and therefore excluding any imports.

[2] For primary products, the quantity consumed is the quantity entering the domestic processing industries, while for processed products, it is the demand of the secondary processing industries, including imports.

[3] The FFSM model cannot represent either exports of processed products or imports of primary products.

Firstly, it should be noted that the total volume of the three primary products supplied (hardwood lumber, softwood lumber and pulpwood-energy wood), which in 2015 was 74.4 Mm^3, is greater than the volume harvested from forests (shown previously). This difference can be explained by the fact that the volume shown in Table 5.3 is actually the sum of four volumes: the volume harvested in the forest, the volume harvested in non-forest environments (e.g. hedgerows), biomass that does not originate directly from the forest (e.g. recycling sawmill residues to produce pulpwood and energy wood) and, lastly, wood from dead trees.

As might be expected, the 'Extensification' scenario only marginally modifies the supply-use balances[20] of the different products in the sector. At an unchanged level of production, there is little reason for the economic equilibrium of the sector to be profoundly altered. Although some changes are perceptible in terms of exports, they ultimately concern only small volumes.

In the case of the 'Intensification' scenario as modelled by FFSM, the combined effect of the demand and supply incentives leads to a consequent increase in the production and consumption of all products in the sector and a doubling of exports, while import levels remain relatively stable. In both absolute and relative terms, the wood energy and pulp and paper sectors show the largest gains, in part due to the stronger incentives that were simulated for these sectors. The combination of incentives and, above all, the inertia of the system as reflected in the model, only slightly modify usage patterns: under these very restrictive assumptions, outlets would therefore remain massively concentrated on energy wood on the one hand and softwood lumber on the other, with paper pulp and panelling lagging far behind[21].

It is important to note that the strong increase in wood product consumption remains compatible with low import levels and sustainable harvesting throughout France.

Impacts of intensified management on the economic performance of the sector

The benefits that producers and consumers could derive from the situation depicted in the 'Extensification' scenario change only slightly by 2050 compared to the present situation (Table 5.4). However, the 'Intensification' scenario, as simulated by the FFSM, would lead to a total sectorial surplus[22] 75% higher in 2050 than in 2015.

Table 5.4. Trends in the economic performance of the French forestry & wood sector from 2015 to 2050 for the 'Extensification' and 'Intensification' scenarios from FFSM (in millions of euros).

		2015	2020	2030	2040	2050
'Extensification' scenario	Consumer Surplus	5,279	5,324	5,377	5,311	5,245
	Producer surpluses	1,912	1,921	1,918	1,964	2,024
'Intensification' scenario	Consumer Surplus	5,281	6,923	8,023	8,926	10,232
	Producer surpluses	1,910	2,030	2,091	2,165	2,372

This strong increase would more strongly benefit consumers (95% increase in thirty-five years) than producers (growth not exceeding 15% over the same period). The implementation of the envisaged public policy measures, which would simply maintain harvest rates, would thus be more favourable to consumers than to producers. This result is important from the viewpoint of political acceptance of such measures.

When comparing the costs of public policies (Table 5.3) with the surpluses to the economic agents of the forestry & wood sector represented in the FFSM model (Table 5.4), it might seem that, compared to the 'Extensification' scenario, the more dynamic trajectory of the 'Intensification' scenario generates a slight decrease in the net social surplus (of around 10%) over the entire period, despite the considerable gains that this trajectory would provide the sector. However, caution must be exercised in interpreting such a result. Beyond the very specific (and costly) nature of the public support integrated into FFSM and the windfall effect that could bring to consumers, FFSM is a model in partial equilibrium: it therefore does not take into account the macroeconomic feedback that could take place with other sectors. In particular, the increase in the consumption of certain wood products, such as energy wood, will partly result in a decrease in the consumption of fossil fuels due to the substitution effect. This substitution is in principle more important in the dynamic scenarios than in an 'Extensification' scenario, due to the increase in consumption levels. However, in a context of uncertainty about the price of fossil fuels, the substitution of fossil fuels by energy wood may result in an additional net surplus gain that FFSM alone cannot represent. In order to test this hypothesis, the FFSM model should be coupled with a general equilibrium economic model explicitly representing all sectors, and in particular the energy sectors.

Conclusion of part II

Each of the three scenarios can strongly contribute to climate change mitigation by optimising different mechanisms. In the 'Extensification' scenario, the main driver is the increasing annual storage in the forest ecosystem, particularly in forest biomass, without increasing storage in products or substitution effects. However, there are indications that this strategy could reach certain limits due to the decline in forest storage capacity as stands densify. Conversely, the ‘Territorial dynamics’ and ‘Intensification’ scenarios rely more on substitution effects to compensate for less storage in the forest, with material substitution playing the dominant role. However, material substitution also presents the greatest uncertainty, as substitution coefficients and, most importantly, their evolution over time is particularly difficult to capture or anticipate. Sensitivity analyses on this aspect have shown that any reduction in greenhouse gas emissions by material substitution would reduce or even cancel out the carbon balance benefits of management strategies aimed at increasing carbon storage in forests. However, given their determinants, such improvements may not occur spontaneously, and must be supported by public policy instruments if the envisaged forest management trajectories are based on maintaining or increasing forest harvest rates.

Furthermore, the role played by the proposed reforestation plan does not become evident by 2050. On the one hand, its effects on forest storage are only likely to be felt beyond the forecast time frame; on the other hand, some of the logical constraints introduced into the programming for this reforestation plan limit the expected gains in forest productivity.

From an economic perspective, while the strategy of intensifying forest management has advantages in terms of both economic and employment gains, significant obstacles have been highlighted by the analysis. Indeed, in the absence of any change in consumption patterns or the French industrial structure, significant direct subsidies would be required to simply maintain today’s harvest rates, which nevertheless correspond to a significant increase in the volumes produced and consumed. Consumption trends do appear to be moving in this direction. However, investment, as well as commercial and support structures, should be strongly stimulated in order to, on the one hand, increase the volumes processed, transformed and marketed and, on the other hand, to shift the balance of uses towards lumber, which is potentially the most advantageous in terms of carbon storage and substitution effects.

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12 Harvest = extraction - farm losses

13 Development of the National Forest and Wood Programme (*Programme national de la forêt et du bois*: PNFB), Working Group (WG) No. 1: Sustainable Forest Management, May 2015, 42 p.

14 Details and stages of this original approach can be found in the annex and in Berthelot *et al.* (2019).

15 By storage, we mean the change in the amount of a stock over a year, regardless of the greater or lesser intensity of instantaneous exchanges between this stock and the atmosphere. A negative value for one of the components means that the stock under consideration has decreased during the year.

16 See Chapter 6 and Box 6.1 for the linkage between the GO+ and MARGOT models.

17 This issue will be explained later, when the results of the economic simulations of the scenarios, carried out with the FFSM model, are presented (Chapter 5).

18 As the base year for these projections is 2016 (and not 2013 as in Figure 1.1), the initial values of carbon storage in the French forestry & wood sector differ slightly from those reported in Figure 1.1.

19 Due to its current methodological limitations, the FFSM model used in Chapter 5 was not able to differentiate the wood use patterns across the scenarios.

20 This implies that, for each product, the sum of usage (consumption + exports) equals the sum of supply (production + imports).

21 Even taking into account the processing coefficients for these products, which are 1.53 for pulp and 1.43 for panelling.

22 The consumer surplus is the difference between what the consumer is willing to pay for a good and the amount actually paid (also referred to as consumer ‘welfare’). The producer’s surplus is the difference between the price at which he was willing to sell the good and the price obtained (the equilibrium price).

Part III

Effects of worsening climate change and severe disturbances on the carbon balance up to 2050

In order to predict the carbon balances resulting from the forest management scenarios, as analysed above, it was assumed that the climatic conditions of recent years would remain constant over the entire 2016-2050 period. However, there is every reason to expect that climate change and its effects on forest dynamics will worsen, which could affect the carbon budgets of each of the management scenarios. Similarly, it is also relevant to consider major biotic or abiotic disasters that could affect French forests between now and 2050, thus affecting one or more components of the sector's carbon balance (Galik and Jackson, 2009; Bradford *et al.*, 2013).

Few previous studies have attempted to introduce these two types of disturbance. Therefore, it is both interesting and innovative to complete the previous simulations by introducing, on the one hand, a degradation of climatic conditions and, on the other hand, various forms of major disturbances that could impact French forests up until 2050. This exercise is particularly delicate and risky to conduct, as there are multiple options available, particularly in terms of the abiotic or biotic disturbances to be addressed. These options relate as much to the nature and magnitude of the potential disturbance as to the timing and frequency of such events. Consequently, the simulation of such scenarios requires a large number of assumptions that can be adjusted many times over. Thus, the following results should be viewed with due caution; they are intended simply to illustrate and therefore stimulate thought on what could happen to the carbon balance of the French forestry & wood sector if, in addition to the management scenarios seen above, a more pronounced deterioration in the effects of climate change or large-scale disasters were to be superimposed on them.

Three types of severe disturbances were conceived and simulated, with each designed to incorporate a cascade of hazards in addition to the ongoing climate change effects. The first involves a large-scale fire episode, which aggravates the impacts on biological growth of a drought (which is introduced to accentuate the effects of climate change). The second is a large-scale storm, such as the Lothar-Martin and Klaus storms in 1999 and 2009, respectively, which devastated French forest areas and was accompanied by outbreaks of bark beetles on coniferous trees and consequent fire episodes. Finally, biological invasions devastating either pines or oaks are simulated.

The impact on the carbon balance of these extreme events or climate changes is then assessed for each of component of the forestry & wood sector. We successively study the effects, on the carbon balance, of a worsening of climate change (Chapter 6), followed by the impacts of the three types of extreme events envisaged (Chapter 7). In both cases, we need to very specifically describe these changes or shocks. As extreme events can occur at any time and take many forms, they must be precisely defined before their impacts on forest dynamics can be simulated and their effects on the carbon balance by 2050 can be established.

Chapter 6

The effects of worsening climate change

Beyond the effects of forest management scenarios, there are strong grounds for examining the role that key factors, such as a worsening of climate change, could play on forest stands and the development of the resource and its uses over the coming decades.

What climate trajectories should be adopted?

The 'current climate', based on the 2003-2013 data series and used in the previously analysed carbon balance projections to 2050, is already somewhat inaccurate owing to a succession of dry years similar to the dry episodes from 2003 to 2006. Using the current climate (average climate over the period 2003-2013) as the reference climate therefore already includes elements of climate change.

However, it was envisaged that the climate situation would deteriorate further over time. To this end, three climate scenarios were analysed for France based on the greenhouse gas emission trajectories defined by the IPCC in its 5th report in 2014: the 'Representative Concentration Pathways' (RCP) 2.6, 4.5 and 8.5 (Moss *et al.*, 2010). They constitute reference climate change scenarios for the period 2006-2100 and are denoted by the level of radiative forcing caused by human activities in 2100 (i.e. 2.6, 4.5 and 8.5 W/m^2, respectively). Radiative forcing is a quantitative concept corresponding to the impact of an emissions trajectory translated in terms of energy radiation at the top of the troposphere in response to a combined change in climate change factors such as greenhouse gas concentrations and the albedo of continental surfaces.

The relevant climate data for mainland France are available at sufficient resolution from the Drias portal of Météo France[23]. They originate from the CNRM-2014 project of the National Centre for Meteorological Research, which simulates daily meteorological data at a resolution of 8 × 8 km over the whole of France. It uses the Aladin regional dynamic climate model (Aladin-Climat v4), which provides simulations for three RCP climate trajectories (Table 6.1).

Table 6.1. Characteristics of the RCP trajectories used in this study.

RCP	Radiative forcing	Concentration (ppm)	Trajectory
RCP-8.5	> 8.5W/m^2 in 2100	> 1,370 $eqCO_2$ in 2100	Growing
RCP-4.5	~ 4,5W/m^2 at stabilisation after 2100	~ 660 $eqCO_2$ at stabilisation after 2100	Stabilisation without overshoot
RCP-2.6	Peak of ~ 3W/m^2 before 2100, then decline	Peak of ~ 490 $eqCO_2$ before 2100, then a decline	Peak then decline

Extracted from the Drias portal, www.drias-climat.fr/accompagnement/sections/175.

RCP-8.5 is the most pessimistic, as it could lead to global warming of between +2.6°C and +4.8°C. The most favourable scenario is RCP-2.6. Of these climate scenarios, only the results of the most severe scenario (RCP-8.5) are retained, which shows marked impacts in comparison with the present. Indeed, the forest dynamics output from the GO+ model (Box 6.1) under RCP-8.5 climate conditions shows a 'deterioration' to those obtained directly from the MARGOT model under current climatic conditions. The RCP-4.5 scenario provided no additional information, while the RCP-2.6 scenario does not significantly differ from the 2003-2013 climate (i.e. maintaining the climatic conditions of the last few years over the entire 2016-2050 period).

Box 6.1. Using the GO+ biophysical model to apply climate effects to forest dynamics.

GO+ is a forest growth, production and management model representing the main biophysical and biogeochemical processes of a managed forest ecosystem. It has been used and developed by researchers at from the *Interactions sol plante atmosphère* (ISPA) joint research unit since 1999 (Moreaux *et al.*, 2020).

GO+ is mainly used to simulate the effects of climate scenarios and forest management at the sub-regional, regional and national scales on the growth and productivity of three key species of production tree: maritime pine, beech and Douglas fir. It typically simulates the functioning of a forest plot comprising a stand of trees, the undergrowth, and the soil, from regeneration to final felling. The model is based on a spatial unit corresponding to a homogeneous patch of forest vegetation, typically one hectare. It operates on an hourly time step, but the main variables of interest are integrated at daily, monthly and even annual scales.

GO+ describes the main exchanges in the soil-vegetation-atmosphere system, namely the energy balance, the carbon and water cycles, and the processes involved: turbulent transfers, heat fluxes, evapotranspiration, diffusion between air and foliage, photosynthesis, respiration, carbon distribution, growth, phenology, mineral immobilisation and exports, mortality, returns to the soil and soil carbon mineralisation. It models vegetation using a two-layer approach: the tree canopy and understorey vegetation.

Vegetation is represented dynamically, with a description of the phenology, senescence and mortality of the two vegetation layers. The effects of forest management operations on the soil and vegetation are taken into account: soil preparation, fertilisation, drainage, removal of undergrowth, thinning, pruning, coppicing, final felling, clear-cutting and harvesting (trunk, branches, foliage, and roots).

Calculating the effect of the future climate on growth

GO+ model simulations enabled the MARGOT resource model to take into account the impact of climate change on stand growth and production. This impact was calculated as the anomaly observed in the annual increase in above-ground biomass per hectare simulated by GO+ between a future period and the reference period of the MARGOT model, i.e. the decade 2003-2013. The anomaly was calculated across a 32 km × 32 km Safran grid in thirteen-year increments covering the period 2005-2095 for a fixed basal area cover, with a defined average density, height and circumference. This calculation was adapted for each of three types of stands, lowland softwood (represented in GO+ by maritime pine), hardwood (represented by beech) and upland softwood (represented by Douglas fir), two useful soil water reserve classes (30 and 80 mm) and two age classes (15 and 40 years for conifers, 30 and 90 years for hardwoods and 20 and 60 years for upland forests). The value of the anomaly was introduced into Margot for the three species groups, taking into account the diameter classes and the useful reserve classes.

Limitations of the GO+ model for extrapolation throughout the country

The major weakness of the GO+ modelling tool is the limited number of species on which it is calibrated in relation to the diversity of French forest resources. When using GO+ to examine the effects of climate change on forest productivity, this limitation can affect the results. Further interaction with ecophysiological models would benefit from its extension to other major French tree species (oaks, spruces, firs, etc.). Further research on developing models calibrated from IFN data that can adjust growth and mortality in response to changing climatic conditions should be pursued in a more integrated manner (Charru *et al.*, 2017).

Combining the GO+ and Margot models to simulate RCP-8.5

The consequences of the RCP-8.5 climate scenario on forest resources were represented in the production and natural mortality parameters in MARGOT. The variations in growth were taken from the results of the GO+ model, and applied to the study areas in MARGOT in a differentiated way according to the location and type of stand. Excess mortality from future droughts also affects mature trees. This is calculated on the basis of mortalities following the summer of 2003, as observed via the systematic forest monitoring network for the quantification of drought effects.

The GO+ forest growth, production and management model depicts the main biophysical and biogeochemical processes of a forest ecosystem for the main productive forest species (i.e. pine, beech and Douglas fir). It therefore allows the analysis of forest dynamics to take into account changes in conditions, particularly climatic conditions (Box 6.1).

On the Drias 'Les futures du climat' (*Climate Futures*) portal[24], drought episodes are defined on the basis of meteorological variables (annual maximum number of consecutive days without rainfall). Modelling with GO+ allows more advanced modelling, by taking into account the water balance of the stands (rainfall, evapotranspiration and drainage), which determines the amount of water in both soils and plants. Its impact on stand productivity is reflected in the following processes:

- reduction of the stomatal diffusion of CO_2 from the air to the plant and reduction of photosynthesis;
- increase in leaf temperature, with consequences for respiration and photosynthesis;
- cessation of growth of tree foliage and undergrowth;
- mortality of understorey plants;
- redirection of plant growth in favour of the root system and to the detriment of the aerial component.

This impact of the drought translates into productivity anomalies. The growth anomalies that GO+ highlights with the degraded climatic conditions of RCP-8.5 have been introduced in the Margot model to modify the parameters that would otherwise have been based on historical data. However, as not all French forest species are modelled in GO+, it was necessary to transpose the results from one species to another. Only data for the three species (beech, maritime pine and Douglas fir) with sufficiently robust calibrations could be used, although these species are not completely representative. Regardless, the results obtained from the 'beech' model were used for all hardwoods, those of the 'maritime pine' for all pines and those of the 'Douglas fir' for all other softwoods.

In addition to the effects of climate on tree growth, the effects of drought on mortality were considered. Drought refers to an extreme water deficit (such as in 2003) or recurring deficits over several successive years. In this case, the regulating capacity of trees is exceeded and permanent damage may occur. Impacts may include embolism in certain tissues, branch mortality, and leaf loss, often translating into a phase of dieback. Extreme conditions may result in excess tree mortality, as in 1976, 1989-1991 or 2003 (Bréda *et al.*, 2006)[25].

Drought-related excess mortality rates were calculated on the basis of past observations within the systematic forest monitoring network (French section of the ICP Forest network, Level I[26]) since 1989. This programme annually monitors the health status of approximately 11,700 trees spread over more than 540 plots organised in a systematic grid of 16 km × 16 km cells. In France, this is managed by the *Département de la santé des forêts* (Forest Health Department) under the ministry responsible for Agriculture.

The impact of drought is quantified in the RCP 8.5 climate scenario in terms of additional mortality, with reference to past observations within the systematic 16 km grid. However, the low density of this network does not allow analysis of tree mortality either in its spatial distribution (by large ecological regions, e.g. Greco) or by tree type. Thus, we were only able to estimate the additional mortality at the national scale for two groups i.e. hardwood and softwood. Background mortality was estimated at 0.15% of stems per year in hardwoods and 0.2% of stems per year in softwoods over the 1989-2015 observation period (Figure 6.1).

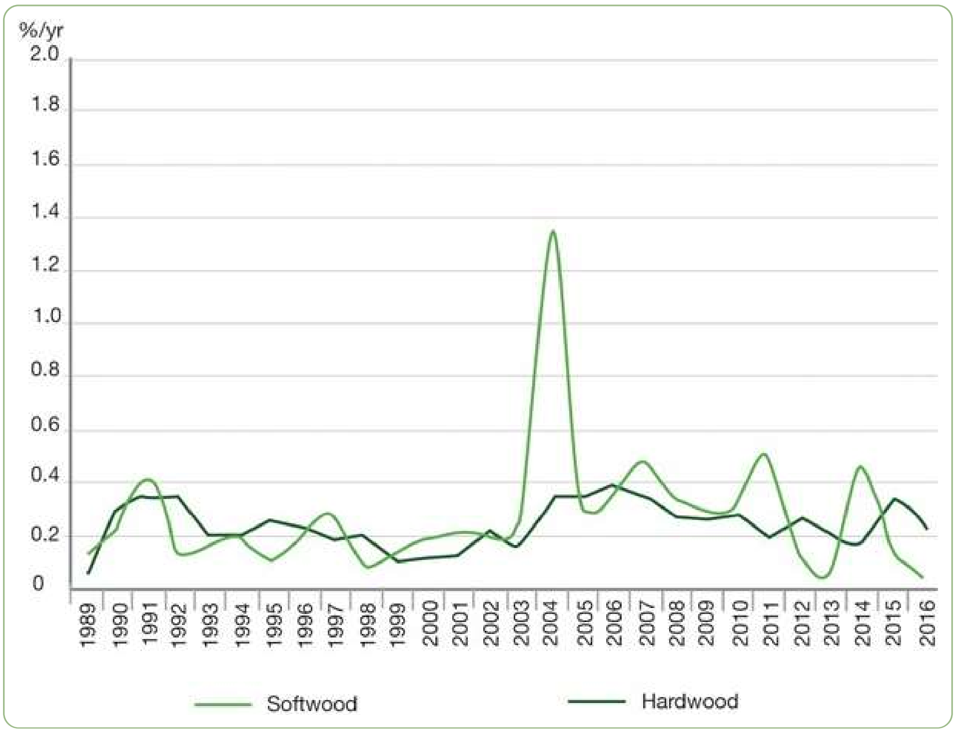

Figure 6.1. Tree mortality rates within the systematic monitoring network since 1989, in % per year (Source: *Département de la santé des forêts* (Forest Health Department), Goudet, 2017).

This additional mortality is integrated without any spatial[27] or temporal[28] distinction. The frequency of years with drought equal to or greater than 2003 was determined from the outputs of the GO+ model under the RCP-8.5 climate forcing. From the first period, a drought of intensity greater than or equal to that of 2003, and therefore likely to induce a dieback, is predicted in more than 90% of cases, with a near- systematic recurrence over several years. The additional mortality of medium and adult trees for each year of the MARGOT projections, over and above the mortality calculated by IGN, is thus 0.13 for hardwoods and 0.76 for softwoods (over 27.5 cm in diameter).

The use of dry and decaying wood by the sector was differentiated between hardwood and softwood species, based on the current use of these by-products. All of the softwood in this category are converted into energy wood and pulpwood, while there is no impact on hardwood product categories. Some of the dead wood remains in the forest, following the same rules as those already defined in the MARGOT model.

The impacts of worsening climate change on forest dynamics and carbon balances

The effects of the trajectories described above on the various components of the carbon budgets of the French forest & wood sector were simulated up to 2050 using the MARGOT model, with certain parameters being adapted using the results of the GO+ model in order to introduce the effects of worsening climate change.

Less rapid carbon storage in the ecosystem

The climate option RCP-8.5, introduced from GO+ into the MARGOT model, resulted in a levelling off of the organic production of hardwoods and a slight increase in that of softwoods (approximately 45 to 55 million cubic metres above-ground volume per year). The organic production of French forests would thus tend to stabilise as a result of a combination of two opposing trends: continued spatial expansion and maturation on the one hand, and increasingly restrictive climatic conditions on the other. Consequently, if the effects of climate change tended to strengthen, accumulation would continue but not accelerate, contrary to the results presented in Chapter 4. The strongly negative changes in productivity trends after 2050 resulting from GO+ point to a worsening of the situation beyond the time frame of this study. This suggests, therefore, that the worsening effects of climate change could increase the vulnerability of French forests by the 2050 horizon.

As a result, the climate option RCP-8.5 would lead to a significant reduction in storage rates (the 40% disparity compared to storage rates under current climatic conditions by 2050), although annual storage in the forest ecosystem would remain positive (Figure 6.2). The differences between the three management scenarios are somewhat reduced, but without changing their order under the current climate. The growth rate of annual storage would slow down considerably under the ‘Extensification’ scenario, it would decrease slightly under the ‘Territorial dynamics’ scenario, and its fall would be slightly more pronounced under the ‘Intensification’ scenario.

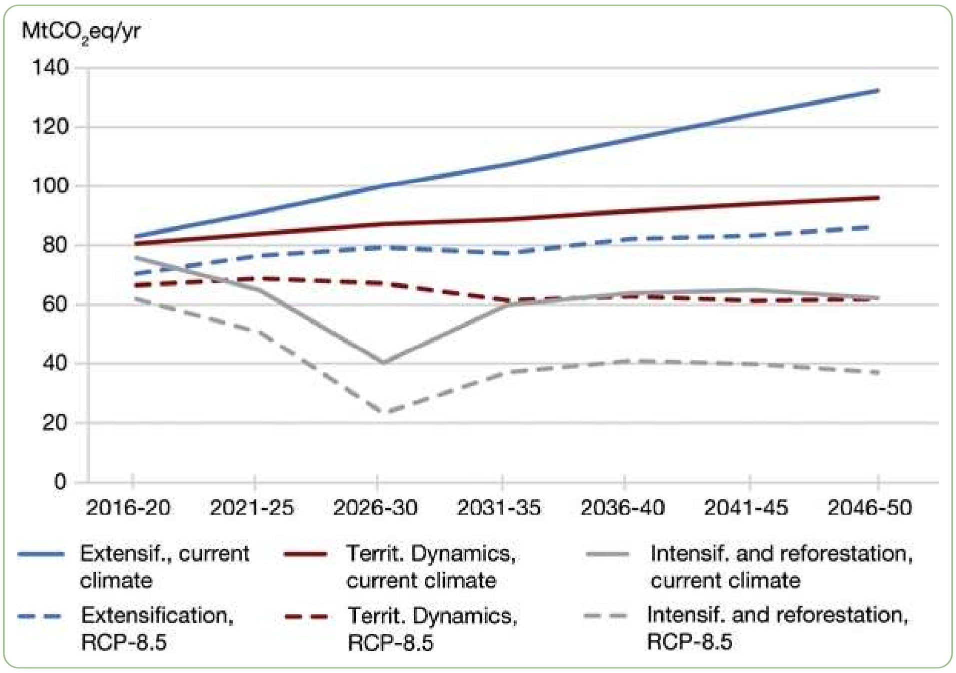

Figure 6.2. Annual carbon storage in the forest ecosystem over the period 2016-2050 under the three management scenarios and two climate scenarios ($MtCO_2eq$/year).

If the effects of climate change worsen, cumulative forest storage over the entire 2016-2050 period would decrease by 27% for the ‘Extensification’ and ‘Territorial dynamics’ scenarios and by 33% for the ‘Intensification’ scenario (Figure 6.3). Total cumulative carbon storage in the forest ecosystem between 2016 and 2050 would vary, depending on the management scenarios, between 2,100 and 3,700 $MtCO_2eq$ under the current climate (Chapter 4), and between 1,500 and 2,800 $MtCO_2eq$ if the effects of climate change were to worsen (RCP-8.5).

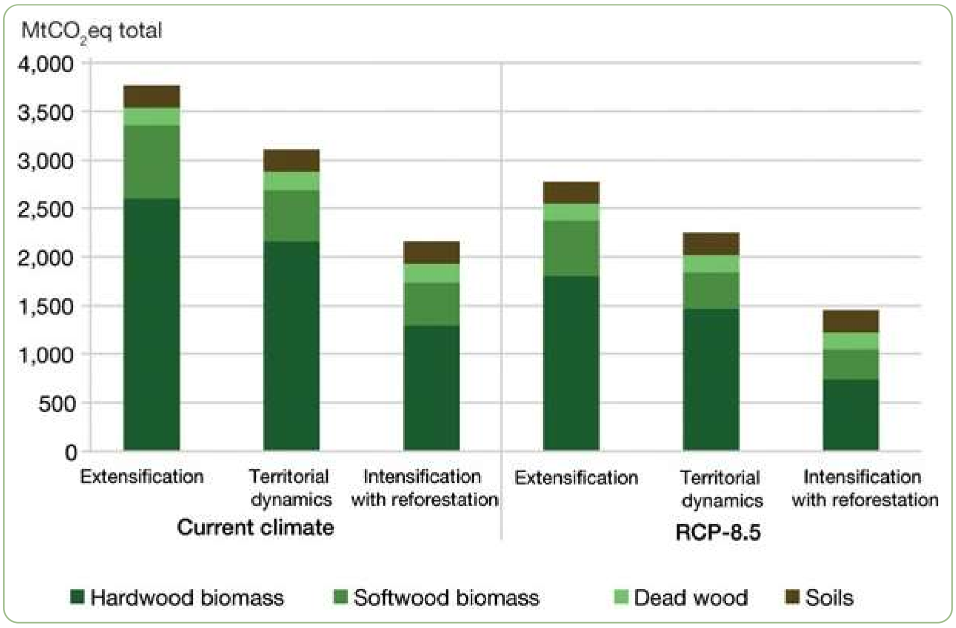

Figure 6.3. Cumulative carbon storage in the forest ecosystem over the period 2016-2050, according to the three management scenarios and the two climate scenarios ($MtCO_2eq$).

These broad trends firstly confirm that, regardless of climatic conditions, forest ecosystems, without even considering wood processing and substitution effects, will contribute significantly to the national greenhouse gas balance up to 2050. However, the size of this contribution will depend very much on the combination of wood management and use of wood, and the mitigative effects of increased climate action.

Breakdown of the harvest by use and storage in wood products

The volumes of wood entering the sector should continue to vary strongly between scenarios (Figure 6.4). If climate change worsens (RCP-8.5), these volumes would change little: they would remain the same as they would be under the current climate for the 'Extensification' scenario and would decrease by less than 10% for the other two scenarios. In effect, the dynamics of storage in forests and harvesting of already mature wood are quite independent over the relatively short period of thirty-five years. Under the assumption of the current climate continuing over the entire study period, the breakdown between timber, industrial wood and wood energy uses could not be clearly differentiated according to the management scenario.

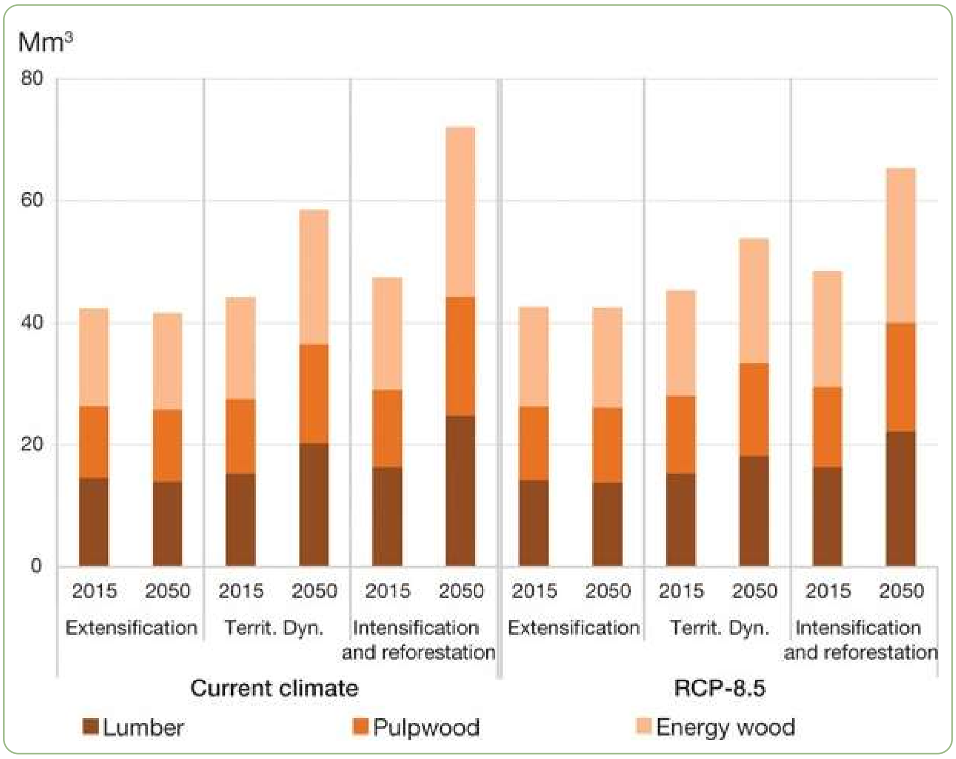

Figure 6.4. Breakdown of wood volumes entering the sector in 2015 and 2050 according to use (lumber, pulpwood and energy wood), by management scenario, and under current climate and RCP-8.5 (Mm^3).

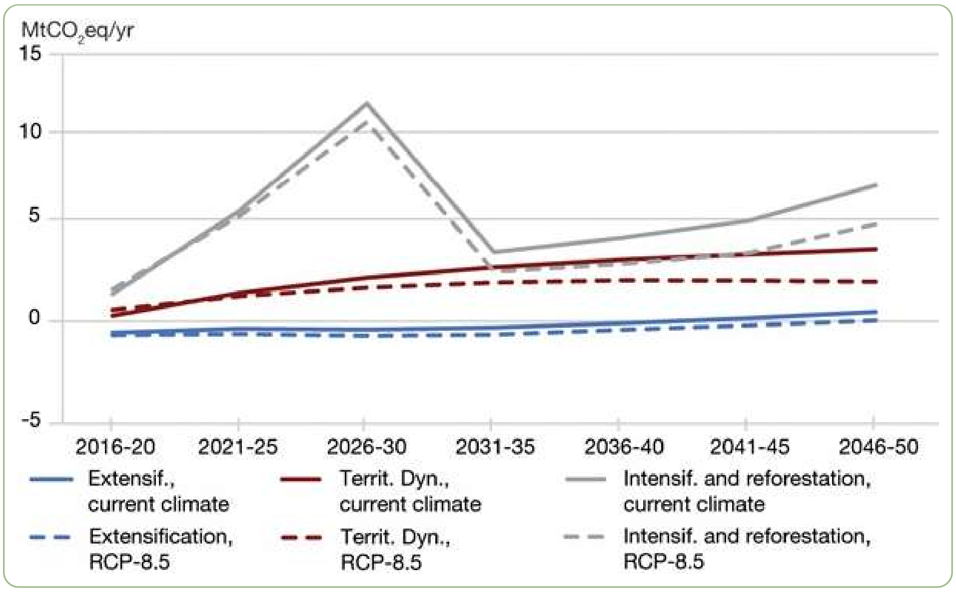

Figure 6.5. Annual carbon sequestration in French wood products according to the three management scenarios and the two climate scenarios ($MtCO_2eq$/year).

Under these assumptions, annual overall sequestration in wood products would remain low, following a progression in line with the harvest rates envisaged for each scenario. It is almost nil under 'Extensification' (where the absolute harvest level remains close to its current value), and approximately 3 to 6 $MtCO_2eq$/year under the other two scenarios. Furthermore, it may slow down somewhat, particularly at the end of the period, if the effects of climate change were to increase (Figure 6.5). In any case, this rate is very low compared to ecosystem storage and substitution effects.

Substitution effects are not greatly impacted by the worsening of climate change

Over the entire 2016-2050 period, the cumulative avoided emissions will range between 1,250 and 2,000 $MtCO_2eq$ depending on the management scenario (Figure 6.6). They would be little affected by a worsening of the effects of climate change (RCP-

8.5). The cumulative emissions avoided would remain unchanged for the 'Extensification' scenario, notably because our assumptions result in constant harvest volumes over time. In the case of the 'Territorial dynamics' and 'Intensification' scenarios, for which the volume of withdrawals is set in proportion to the change in standing stocks, the cumulative total would be somewhat lower in a worsened climate context than it would be if the current climate were to be maintained. Nevertheless, the differences in avoided emissions would, in these cases, be quite small (in the order of -3% and -4%, respectively). The absence of a significant effect from worsening climate conditions on the total harvest volume by 2050 can be largely explained by the time lag between the period in which trees grew to maturity for a harvest between 2020 and 2050 (fifty to one hundred and eighty years depending on the species) and the future climate, which has a greater effect on the growth of trees that can be harvested in the longer term.

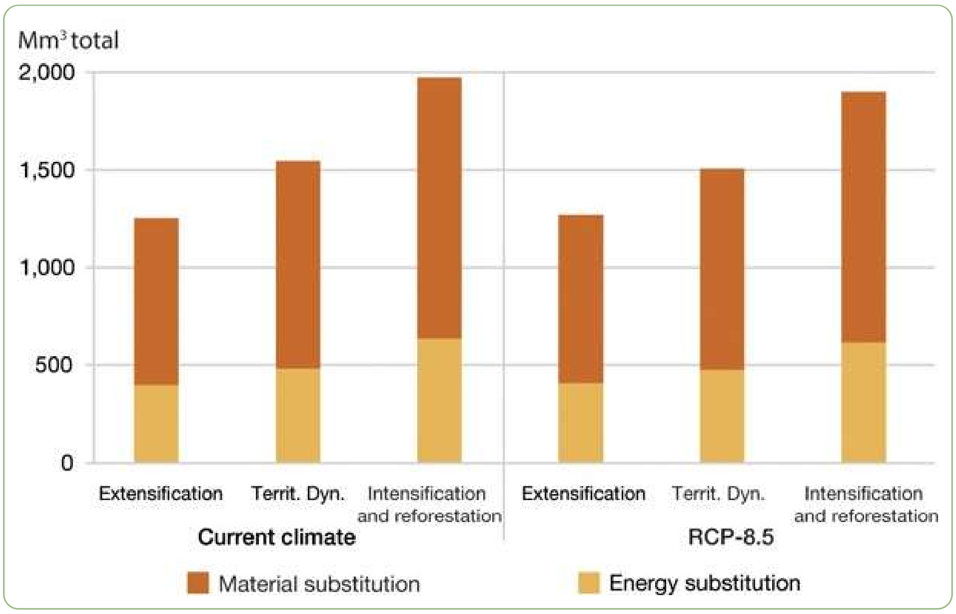

Figure 6.6. Cumulative CO_2 emissions avoided by substitution effects over the 2015-2050 period under the three management scenarios, given both the current and RCP-8.5 climatic conditions (in $MtCO_2eq$).

Thus, as forest management intensifies, the use of substitution effects, which are more robust than ecosystem carbon storage to the impacts of climate change, could more readily cushion the decline in the contribution to climate change mitigation.

Reduced carbon balances for all scenarios

Despite the uncertainties regarding carbon storage and emissions avoided in certain components of the sector (effects of stand density on changes in standing storage, or changes in wood-material substitution coefficients – see Chapter 4), it is nevertheless possible to compare carbon balances according to the two climate hypotheses considered here: continuation of the current climate versus worsening of climate change according to the RCP-8.5 trajectory (Figure 6.7).

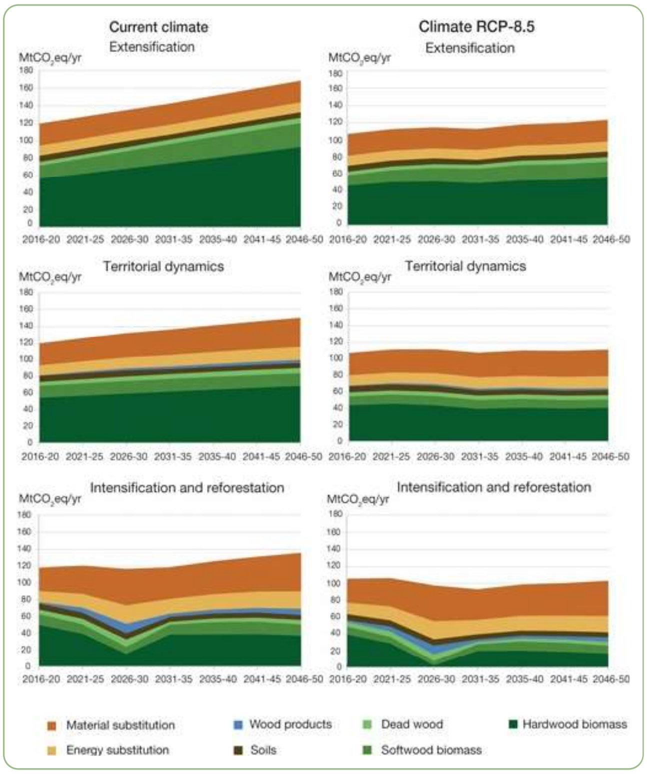

Figure 6.7. Comparison of the carbon balances of the French forestry & wood sector under the three management scenarios, and under current climate and RCP-8.5 ($MtCO_2eq$).

The increase in annual carbon balances would clearly slow down under the assumption of a worsening of the effects of climate change, regardless of the management scenario considered. In all cases, carbon budgets are almost constant over the simulated period (2016-2050). This constancy is primarily due to the combination of one factor remaining positive (the trend towards expansion of areas, entry into production of young stands) and another factor (climatic) which tends to be unfavourable to forest productivity. These factors are accompanied by an almost unchanged storage in wood products compared to that under the current climate, and by substitution effects of the same magnitude as under the assumptions in Chapter 4.

However, the very early manifestation (from the period 2015-2028) of the loss of production is a direct consequence of the assumptions used in GO+. In view of the importance of hardwoods to the overall French resource, the average production rapidly decreases over most major ecological regions (GRECO) due to the application of the ‘beech’ model to all hardwoods. Beech is particularly sensitive to drought, which may lead to an overestimation in the model of drought-related hardwood mortality, and therefore a possible underestimation of the forest carbon sink. Moreover, the additional drought-related mortality reflects a factor applied from the initial period until 2050: that simulated future droughts are therefore largely as severe as the 2003 drought. This set of factors probably contributes to overestimating the climate impact and underestimating the future level of the sink for all of the scenarios considered here.

In any case, climatic anomalies affecting production and mortality lead, from the beginning of the simulated period, to a rapid divergence between the effects of the current climate and the RCP-8.5 trajectory. This strong divergence illustrates the issues involved in the adaptation of forest stands to climate change and should encourage thought on adaptive strategies. One consequence of this loss of production is that the structure of the carbon balance of the sector will be significantly modified in relation to that under current climatic conditions. Thus, the relative proportion of substitution effects in the carbon balance would increase significantly: in 2050, it would represent 58% of the annual carbon balance under the ‘Intensification’ scenario (compared to 49% without a change in climate from the present), 41% for ‘Territorial dynamics’ (compared to 33% under the current climate) and 30% for ‘Extensification’ (compared to 22% under the current climate). Conversely, the share of carbon storage in forest biomass would tend to decrease sharply to 26% in 2050 under the ‘Intensification’ scenario (compared with 37% under the current climate), 46% under ‘Territorial dynamics’ (compared with 57% under the current climate) and 60% under ‘Extensification’ (compared with 70% under the current climate). Increasing or maintaining significant harvest levels increases their importance in the overall carbon balance. It should be remembered that the benefits of forest storage are always reversible, as they are exposed to hazards (all the more so if the local sector is ill-prepared for salvage harvests), whereas those provided by the substitution of materials or energy are cumulative and permanent. Thus, strategies whereby forestry mechanisms for climate change mitigation focus on storage in forests may be undermined by the effects of worsening climate change, and further exacerbated by additional major disturbances.

Chapter 7
Estimating the impacts of severe forest disturbances

Severe disturbances have a structuring effect because, when on a large scale, they modify ecological and/or socio-economic dynamics in the long term, as has been the case on several occasions in recent decades.

For fifty years, storms and fires in Europe have destabilised traditional management methods. The occurrence of a major disaster similar to those which have plagued the North American continent for the past twenty years (mega-droughts, pine bark beetles, fires), would lead to a system shift that would need to be considered at both regional and national levels. Similarly, the risk of major biological invasions could abruptly slow the development of well-established species. In forestry, as in all other fields, when it comes to anticipating such combinations of risks and the associated shocks, expertise is still poorly developed at the international level, with researchers trying to understand these situations as they arise. Given the importance of the potential impact of such phenomena on the carbon storage capacity of the forestry & wood sector, it was felt necessary, albeit risky, to engage in a multi-risk forecasting initiative, bringing together specialists in the various hazards and their impacts.

Why include severe disturbances in simulations?

French forests are regularly subject to biotic (insects and pathogens) and abiotic (drought, frost, storms, fire) hazards, the knowledge of which enables the risk to be estimated. Indeed, the notion of risk can be defined as the interaction between three components:

- the frequency and intensity of the hazard;
- he vulnerability of the system, which defines the extent of the damage caused by the hazard;
- the ecological and socio-economic impact on the system at risk, i.e. the loss related to the damage as a function of the value of the system (IPCC, 2014).

The frequency and intensity of hazards could increase as a result of climate change (Lindner *et al.*, 2010) or continued intense international trade (Fisher *et al.*, 2012), and the vulnerability of forests could also increase without the hazard itself being directly modified (e.g. storms).

Hazards that threaten forests directly compromise their capacity to provide goods and services, but also increase vulnerability to other natural hazards such as floods, pollution, avalanches, landslides or rock falls that threaten other human concerns (Landmann and Berger, 2015).

While there has already been an increase in the fire problem in Europe, due to an increase in wildfire weather risk in some southern European countries and, in particular, in the Iberian Peninsula (Piñol *et al.*, 1998; Pausas, 2004), the fire situation in France appears at present to be under control. The analysis of forest fire statistics in Mediterranean France over the historical period covered by the Prometheus model shows a downward trend in the areas burned annually, with annual averages per decade falling from over 30,000 ha between 1974 and 1983 to just over 7,000 ha over the last decade. These positive results have been achieved while the fire risk has increased over the past decades (Chatry *et al.*, 2010; Fréjaville and Curt, 2017). This success can be attributed in part to the combined effects of prevention and control measures in France and, in particular, to the effectiveness of the strategy for dealing with emerging fires (Ruffault *et al.*, 2016). Nevertheless, these averages hide very strong interannual variations, with record highs such as in 2003, which shows that this favourable result is the result of a fragile balance where the defence and response can be overwhelmed by an exceptional weather situation.

What predictions do the models make regarding the risk of forest fires until the end of the century? Bedia *et al.* (2014) calculated different indicators including the Fire Weather Index (FWI) for different countries on the northern Mediterranean shore for the historical period, and then by implementing a series of climate models for three future periods (2011-2040; 2041-2070; 2071-2100). The study firstly shows that the FWI for France is below the level of the other southern European countries and that it would remain so, but would nevertheless double by 2100. Chatry *et al*. (2010) estimated that the areas at risk of wildfire, which currently account for a third of the heathland and forest areas of metropolitan France, would increase by 30% by 2040 to reach half of the forest area by 2050. Fargeon *et al*. (2020) confirmed the predicted increase in fire danger in France by 2100 and specified the confidence levels of these predictions according to the regions. With regard to the length of the fire season, France starts from a much lower level than other southern European countries (2 to 3 months in summer), but would catch up to these other countries within 80 years. This would involve a doubling of the risk period, with more late winter, spring and late season fires in the autumn (Bedia *et al.*, 2014).

As regards biotic risks to forests, forest pests and invasive pathogens have been exacerbated by the increase in trade (Roques *et al.*, 2010; Santini *et al.*, 2013). The chestnut gall wasp, *Hymenoscyphus fraxineus* fungal dieback in ash, phytophthora disease in alder, box tree moth, *Phytophthora ramorum* disease on larch, and the Asian long-horned beetle, are all examples of recent establishment and spread in metropolitan forests, which has been facilitated by newly favourable environmental conditions (Robinet *et al.*, 2012). The risk of biological invasion is also influenced by climate change (Bellard *et al.*, 2013).

In addition to invasive species, recent studies show how climate change could lead to damage by native insects and pathogens. Increased frequency or intensity of droughts could result in waves of dieback, and increase the susceptibility of trees to many parasites such as bark beetles or Sphaeropsis (Desprez-Loustau *et al.*, 2006; Fabre *et al.*, 2011, Jactel *et al.*, 2012). Robinet *et al.* (2015) note that global warming could lead to an increase in the number of generations and the reproductive performance of insect pests, particularly bark beetles. Higher temperatures could also favour the expansion of insect and pathogen ranges, as observed for the pine processionary caterpillar (Battisti *et al.*, 2005) and *Phytophthora cinnamomi* mould (Bergot *et al.*, 2004).

Therefore, broadly speaking, some forest hazards are currently under control except in extreme weather conditions (fires), while others have already increased over the past decades (droughts, and insect and pathogen invasions) or have caused significant damage (storms). All are expected to increase in the medium to long term as a result of climate change or changes in the forest structure.

In addition, interactions between hazards have already been observed, which may lead to amplification effects, which suggests that risk cascades should be considered as a type of system (Marçais and Bréda 2006; Jactel *et al.*, 2012; de la Barrera *et al.*, 2018).

These hazards cause potentially significant mortality over and above normally observed background mortality (<1%). This can impact the ability of forests to store carbon (Kurz *et al.*, 2008) and can challenge existing management and adaptation measures. Therefore, the inclusion of major severe disturbances that disrupt forest dynamics in the simulations is justified.

Three scenarios involving cascading risks

It was decided to include a combination of different existing risks, the effects of which may be amplified with climate change, in order to integrate the interactions between them. This is why some of these risks are not treated in isolation from each other but rather integrated into scenarios

The selected hazards can strongly impact wood production through a significant reduction in growth or mass mortality (with or without possible regeneration) over large areas (regional or national scale). In addition to drought, which has already been integrated into the climate options, the following hazards were chosen: storm, fire, bark beetles, and insect or pathogen invasion. Some of them have been combined: fires occur in connection with drought, while storms are followed by bark beetle outbreaks and fires. For these two latter combinations, the intensity of the hazard is modified by the climate scenario. In contrast, biological invasions were treated in isolation and considered independently of the climate option and other hazards.

Numerous different major disturbance scenarios could be envisaged, and they could vary in many dimensions. By combining all of the options (nature of the initial extreme event, cascading of risks created, scale and location of the disturbance, frequency and duration of disturbance episodes, etc.), an infinite number of equally credible scenarios could be considered. Therefore, choices were required, with the necessity of specifying a set of parameters to describe the disturbance as well as the full range of consequences on both the French forestry & wood sector and its carbon balance. We have drawn on previous, large-scale extreme events (which have been studied and documented) in order to provide a sound basis for the assumptions about the conditions for and consequences of these events. These scenarios should therefore be considered as illustrations of how the occurrence of extreme events, which are very rarely considered in this type of exercise, could affect the carbon balance of the sector.

Fires following drought

Description of the severe disturbance

The reference year for this scenario is 2003, which characterises a catastrophic ‘forest fire’ season. This is the record year in terms of total area burnt, both at the South-East regional level (61,424 ha - source Prometheus) and at the national level (73,278 ha - source European Forest Fire Information System, EFFIS). The scale of the fire events of 2003 was due to the exceptional heat wave and drought in the summer of 2003.

The total area burned in a year can result from several hundred fires of highly variable proportions, which ranged in 2003 from 1 to 6,744 ha. This exceptional fire season revealed the same rule that governs all fire season totals (even the weakest), namely that a few large fires account for the bulk of the total. These fires represent what can be described in the French context as mega-fires, and they develop when there is a total loss of control by the fire prevention and control system, with virtually no effective protection of forest areas. During these events, the fire-fighting forces focus almost exclusively on the protection of people and dwellings and other human assets (agricultural or industrial buildings, transport infrastructure). The year of 2003 also serves as a reference for mega-fires as, according to the Prometheus Database, three of the ten fires since 1973 that burned over 5,000 ha occurred in this year.

This led to the 2003 fire hazard level being considered as the reference threshold for the ‘drought then fires’ scenario. These risks occur throughout the country in July and August, during which, historically, most of the damaging fires occur. This events are applied to both climate scenarios: current climate and RCP-8.5.

The scale of this severe disturbance

The monthly average FWI (Fire Weather Index)[29] for the whole of France was calculated with GO+ for the months of July and August 2003 over the Safran[30] 8 km × 8 km grid using observed weather data from 2003. The average FWI across the Safran grid tiles for July and August 2003 were 9.77 and 15.62 respectively, i.e. an average of 12.69 over the two months. This latter value was chosen to represent the reference fire hazard for France.

The monthly FWI was also estimated for all years from 2017 to 2050 using weather data simulated with the CNRM regional dynamic model Aladin (Aladin-Climat v4) based on the RCP-8.5 climate scenario. The highest yearly value of the FWI averages for July and August over the same period was 30.42, which represents a fire danger 2.4 times higher than in the summer of 2003. Applying this exacerbative factor to the total national surface area burnt in 2003 (73,278 ha - source EFFIS), the estimated total surface area burnt during the ‘drought then fires’ disturbance amounts to 175,000 ha. This represents the total surface area of all individual fires from a few hectares to several hundred or even thousands of hectares.

Spatial and temporal aspects

The occurrence of the extreme drought that triggers the ‘drought then fires’ event was arbitrarily set during the 2026-2030 five-year cycle of the Margot model so that it would occur early enough in the period studied (2017-2050) to provide a sufficiently long post-disturbance period to assess its effects.

Particularly under the climate scenario RCP-8.5, an extreme climate with a succession of dry years is expected to occur, as in 2003-2006. Each disturbance would certainly be on a smaller scale than the one envisaged here, but their cumulative effects could be greater, not to mention the destabilising effect of this recurrence for the forestry industry and its sector, which could lead to an aversion to undertaking activities and thus paralyse initiatives.

The location of the areas in metropolitan France to be impacted by fires was determined by selecting Safran grid cells with the highest fire risk (FWI > 29.5). The forest areas actually impacted were then determined using the National Forest Inventory by constructing an empirical index of the increase in the fire sensitivity of forest formations.

To define the total surface area burnt, priority was given to the inventory sites with the highest sensitivity to fire up to the equivalent of 75,000 ha and 175,000 ha, under the current climate and RCP-8.5, respectively.

The empirical index of increased fire sensitivity of forest formations was constructed by the INRAE research group Ecology of Mediterranean Forests Unit (URFM) and IGN on the basis of a selection of variables measured at National Forest Inventory sites[31].

Impacts on the forest and the sector

Figure 7.1 shows the distribution of fires in the 'drought then fires' scenario under the RCP-8.5 climate projection.

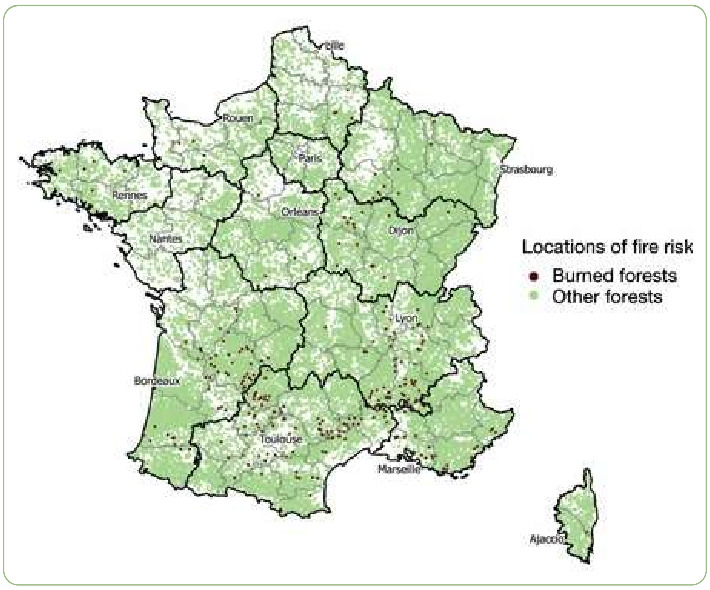

Figure 7.1. Location of burnt inventory sites for the event scenario 'drought then fire' under the RCP-8.5 climate scenario.

In each burnt area, it was assumed that all trees would be killed. The volume of dead wood resulting from the fires was evaluated by the MARGOT resource model, which also provides the volumes of dead wood by dominant species. The markets for burnt wood are limited due to the carbonisation of the trunks, but they can nevertheless be used in particle board or for wood energy.

Storms, bark beetle attacks and fires

Description of the severe disturbance

The aim here is to describe a nationwide winter storm event leading to an outbreak of bark beetles on pines and spruces followed by a catastrophic fire season the following summer. The extreme severity of this disaster relates to the area of forest affected by the storms and the additional wood losses due to bark beetle outbreaks and fires. The Lothar and Martin storms of 1999 were chosen as a reference, as these two storms, which followed each other 2 days apart, destroyed more than 240 million m^3 of wood in 15 countries across Europe, including 176 million m^3 in France, i.e. around 3 years' worth of harvest. This scenario is addressed using current climatic conditions and under RCP-8.5.

The magnitude of the storms was not changed in the RCP 8.5 scenario. Indeed, changes in the frequency and intensity of extreme winds due to climate change are less well known than projections of temperature changes. On the other hand, studies concur that the vulnerability of forests to storms would be increased by several phenomena related to climate change, such as higher temperatures and precipitation during winter, which would reduce the quality of tree anchoring. Likewise, the RCP-8.5 scenario risks aggravating damage due to bark beetles (effect of drought and temperature) and increasing the area affected by fires.

Spatial and temporal aspects

The timing of the ‘Storms, bark beetles and fires’ event was arbitrarily set during the 2026-2030 five-year cycle of the MARGOT model. This was sufficiently early during the simulation period of the study (2017-2050) to allow the effects of this cascade of impacts to be observed under the different management scenarios.

Winter storms from October to January were in fact the most damaging in Europe over the period 1950-2000 (Gardiner *et al.*, 2010). Bark beetle outbreaks are generally observed as early as the summer following the storms, with a concentration on broken stems and windfalls and then, in subsequent years, on windfalls and trees left standing. Outbreaks of bark beetles on pine trees do not last more than three years (Nageleisen, 2009). In contrast, outbreaks of bark beetles on spruce trees can persist for up to ten years (Grégoire and Evans, 2007; Kärvemo and Schroeder, 2010).

As stated above, for the purposes of the study and to simplify the analyses, only one ‘storms, bark beetles and fires’ event was scheduled during the selected simulation period. To define the storm zone, we selected IGN categories with pine and spruce as the dominant species in order to simulate the strongest possible impacts of bark beetle outbreaks.

On the basis of this selection of IGN forest types, a south-west to north-east trajectory from the Charentes was proposed. Extratropical storms tend to follow a course along a line of lower pressure, extending to a greater or lesser extent around this line. They form in the North Atlantic and generally weaken as they reach the coastline. These storms therefore mostly originate from the west and also strike northern England, northern Germany or Scandinavia.

The area affected by the storms was chosen using a catalogue of data on major storms in Europe over the past 50 years (Gardiner *et al.*, 2010). A total area of between 700,000 ha and 1,000,000 ha, corresponding to a strip 50 km wide and 200 km long, was chosen to be affected, and represents the largest area impacted by a storm in Europe during this period (1 million ha for Lothar and Martin in 1999).

Impacts on forests

A primary zone represents the centre of the storm (orange zone in Figure 7.2), where the rate of damage (windfalls + broken stems) is greater than 40%. It is assumed that the affected areas will be subject to total clear-cutting. Adjacent to this primary zone is a peripheral zone where stands are less than 40% affected. This zone of secondary damage (blue zone in Figure 7.2) covers an area of approximately 685,000 additional ha.

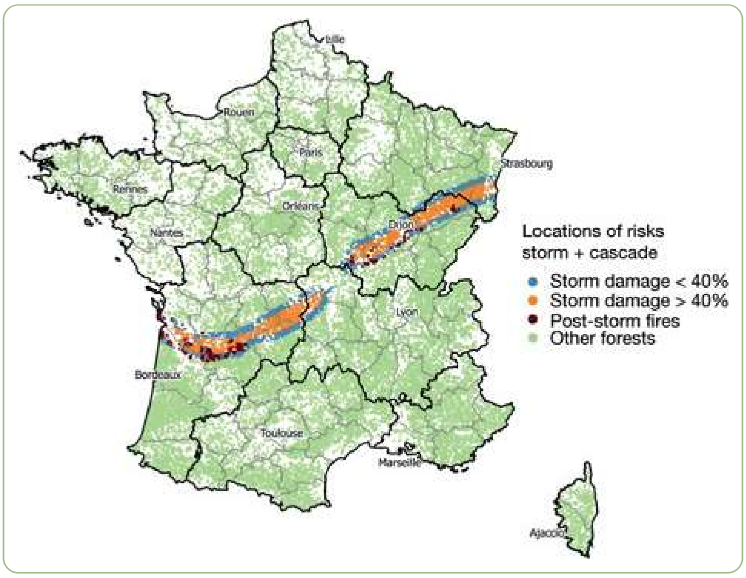

Figure 7.2. Envisaged storm path for the study, with the locations of post-storm fires.

Estimates of wood volumes destroyed by the storm were calculated using the ForestGales model, with Margot providing volumes by tree species and diameter class at the time of the outbreak of the event. The ForestGales model was used to calculate the critical wind speed required to uproot or break trees in each of the defined categories (species × diameter)[32]. The volume of wood destroyed, either by windfall or broken stem, was obtained according to the species and diameter category for each of the two storm damage zones.

After calculating and allowing for the distribution of species, the percentage of windfallen trees would be 43% in the orange zone and 16% in the blue zone. The proportion of windfall and broken stems following storms is important when considering the loss of quality material and thus the potential uses of this damaged wood. These percentages of damaged wood by volume are not affected by the RCP-8.5 climate projection.

The fuel complexes generated by storms (high levels of dead material in all diameter categories, low water content within the fuel, high horizontal and vertical fuel continuity) are highly favourable to the spread of the fire, but also to a more complete combustion, which lasts longer behind the active fire front. In view of the considerable necromass generated by storms (broken stems, windfalls, bark beetles) and the favourable structure of these vegetation complexes for fire propagation, it was decided to focus the fires exclusively within the storm track (blue and orange zones). Furthermore, the difficulties of fire-fighting in areas containing post-storm vegetation and the resulting damage to the networks and infrastructure supporting fire-fighting further increase the vulnerability of these areas to fire. Forest areas that may have been burnt in non-storm areas have therefore been purposely omitted in this extreme event scenario.

Within the storm path, forest areas that were partially (blue zones) or completely (orange zones) impacted were all considered to be equally highly vulnerable to the outbreak and spread of fire, with no need to further distinguish them by an empirical index of increased fire sensitivity. For this extreme event scenario, only local drought, assessed by means of the Fire Danger Index, was used to locate affected forest areas. The Safran meshes with the highest FWI were selected until they reached a total of 75,000 ha under the current climate and 175,000 ha under RCP-8.5. This choice was previously discussed in the ‘drought then fires’ disturbance scenario.

It should be noted that the immediate loss of carbon during combustion was not factored into carbon balance calculations, whether for the part recovered as lumber, pulpwood or fuel wood, or for the burnt wood left in the forest. Post-storm fires are extremely dynamic, and produce more charcoal than conventional wildfires. However, recent studies (e.g. DeLuca and Aplet, 2008) highlight the very long lifetime of carbon sequestered in charcoal and suggest that this should be better reflected in the carbon budgets of forest ecosystems subject to more severe fire regimes as a result of climate change. However, the half-life of burnt wood abandoned in forests has not been changed (set at 30 years), as there remains little information on the assessment of the amount of charcoal produced in relation to non-carbonised necromass remaining in forests, especially in the case of post-storm fires.

Fire can also be expected to destroy wood storage areas and areas at the edge of plots where wood is awaiting removal, thus contributing to further carbon loss. Long-term storage facilities that ration the supply of wood to processing companies may also be impacted by fires if they lack permanent sprinkler systems. Within the burnt areas, the mortality of trees that survived the storms was considered to be total.

The analysis of damage to pine and spruce trees by bark beetle outbreaks was the subject of a species-specific literature search (pine stenographer beetle or European spruce bark beetle). It is estimated that, under the current climate, this damage would vary from 6% to 12% of stems depending on the bark beetle species and the area of damage. Under the RCP-8.5 climate projection, the damage related to bark beetle outbreaks is 1.7 times greater [33].

Post-disturbance perspective

Experience from recent storms shows that markets for broken stems are limited to particle board and energy wood, and that the volumes harvested are of lower quality. The storage of wood for some years affects the thinning of green wood during this period. Exports are stronger but, in general, prices slump. There is also a decrease in harvests in non-impacted neighbouring regions concurrent with a halt in green wood harvests in impacted areas. Markets for burnt wood are limited due to the carbonisation of trunks, but they can nevertheless be exploited for particle board or wood energy.

Biological invasions affecting oaks or pines

Description of the severe disturbance

The envisaged biological invasion (fungus or insect) would result in high mortality of recruits, more moderate adult mortality and significant growth losses, with some outbreaks commencing at the beginning of the study period and then spreading throughout the country. The dispersion of the parasite as well as the dynamics of tree mortality and loss of growth as a function of the duration of its presence were based on observations from the outbreak of *Hymenoscyphus fraxineus* that caused ash dieback in France.

One of the characteristics of the 'biological invasion' event is that there is no interaction with other risks (droughts, storms or fires) and it will therefore not include a cascade of risks. As a result, this biological invasion scenario will only be simulated under the current climate, but it will be designed in such a way as to impact species of major importance.

Two types of biological invasions were simulated, with one impacting oaks and the other pines. Two levels of severity were applied to each of these, with more severe invasions impacting more species. In the case of oak infestations, regardless of the MARGOT forest class in which they are present, the severe scenario impacts common, sessile and pubescent oaks, while the more moderate scenario only affects common oaks. For pines, regardless of the MARGOT class in which they are present, the severe scenario impacts Aleppo, maritime, black and Scots pines, while the more moderate scenario only affects maritime pines.

Spatial and temporal aspects

In simulating the outbreaks, the rate of spread was set at 50 km/year. The initial outbreak was located in north-eastern France for that affecting oaks and in the south for that affecting the pines, with multiple initial foci (Figure 7.3).

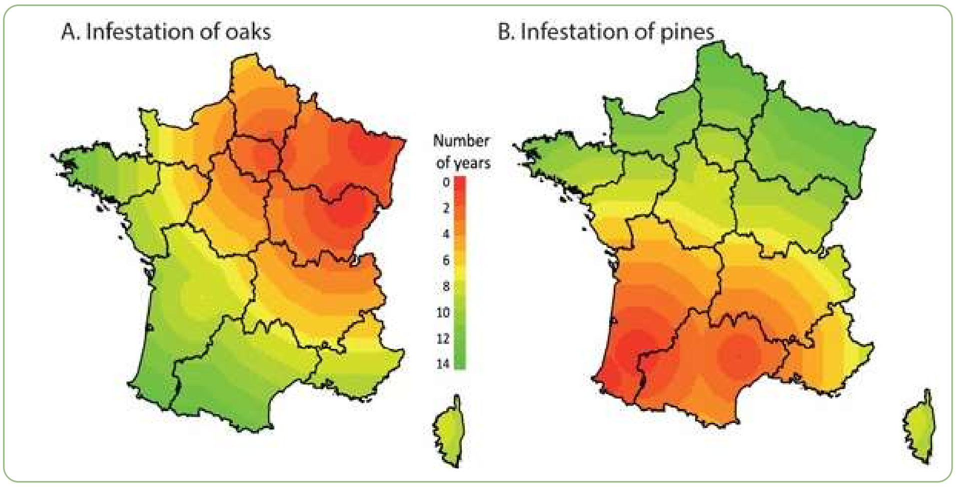

Figure 7.3. Spatial and temporal spread of the invasive parasite causing damage or loss. A. Oaks, B. Pines.

The MARGOT forest classes are impacted according to the proportion of IFN points forming the class affected by the invasive parasite, and the duration of its presence. Only some species in the layer are affected by the invasion (pines or oaks), which can be distinguished from the other species. Growth, mortality and regeneration of non-impacted tree species follow the normal patterns for that forest class, but for impacted tree species these parameters will decline, as described in the next section. The total regeneration in a forest class is calculated automatically based on the change in its basal area[34]. It therefore increases in the event of high mortality, but will be concentrated in favour of non-affected species. This leads to a significant compensation mechanism in favour of the species that currently coexist with the oaks and pines. On the other hand, it was decided not to simulate the complete replacement of species in the event of stands decimated by the invasion, as this could not be achieved in the time allowed. However, we will identify the areas of stands that would be devastated by the invasion.

Impacts on the forest

The impacts will initially involve loss of growth, calibrated on the basis of *Hymenoscyphus fraxineus*, an ash parasite (Muñoz *et al.*, 2016). These losses are calculated as a function of the induced dieback, which depends on the duration of the parasite's presence. Mortality, which is significant, depends on the diameter of the relevant trees: it is high for trees of 5-25 cm diameter, and more moderate for those with a diameter greater than 25 cm. Regeneration of the impacted species occurs according to the normal patterns for that forest class, but in proportion to the share of the impacted species in the 10-20 cm diameter class after taking into account invasion-related mortality. This regeneration takes place through conversion to the other species in the class. The high seedling mortality linked to the invasion is therefore taken into account in an indirect and conservative manner.

The severity of this type of extreme event depends on the following three elements:

– speed of the invasion: A realistic but high-impact invasion was required. We therefore chose a rate of 50 km per year, reflecting the case of the fungus causing ash dieback. Multiple initial outbreaks were simulated, which is often observed in biological invasions;

– importance of the impacted species. The species affected (oak or pine) determine the severity of the disturbance. This type of invasion, which seriously jeopardises the survival of trees of certain species, has so far only affected less important forest species in Europe (Dutch elm disease, red band disease on Corsican pine and Hymenoscyphus fraxineus on ash trees). Certain mechanisms may limit the risk of an invasion of a major tree species by a very severe pest. Indeed, as is often the case for major species, tree species occupying a large surface area in a given region display both genetic diversity and a stronger parasite burden (insects, microorganisms) (Brändle and Brandl, 2003). As a result, they are more likely to have already been affected by a parasite phylogenetically close to the invasive parasite and thus to exhibit pre-existing resistance. Similarly, there is a greater chance that natural enemies of the invasive parasite (predators, parasitoids, mycoparasites, mycoviruses) will be present in the invaded ecosystem. However, this does not eliminate the risk. For example, chestnut trees, a major forest species in north-eastern North America, have been largely eliminated from these ecosystems by *Cryphonectria parasitica* and *Phytophthora cinnamomi* (Anagnostakis, 2001). In other regions of the world, moreover, there are known parasites that are very aggressive toward our pines and oaks. A classic example is the agent of American oak wilt, *Ceratocystis fagacearum*, a fungus close to the agent of Dutch elm disease (MacDonald *et al.*, 2000). Similarly, the emerald ash borer, of Asian origin, was accidentally introduced into the United States in the early 2000s, causing the death of millions of trees and threatening the survival of all *Fraxinus* species (Poland and McCullough, 2006);

– level of growth loss and mortality. The impact of the parasite on these factors is the determining factor in assessing the severity of the event, but for which little information is available. Significant losses in growth were simulated, corresponding to a parasite reaching a very high prevalence and severity, but with an average impact on growth (Jacquet *et al.*, 2013; Twery, 1991). Mortality will also be fairly high. However, it will be far lower than that observed for Dutch elm disease (Swinton and Gilligan, 1996) and slightly lower than that observed for sudden oak death in California (Meentemeyer *et al.*, 2008).

Modelling severe abiotic and biotic disturbances in MARGOT

This approach involves creating, for each of the 116 forest classes in the MARGOT model, sub-domains separating the resource affected by these disturbances from the remainder of the resource. The growth and mortality parameters of these sub-domains are impacted at the time of the disturbance according to the assumptions specific to each disturbance scenario described above.

One unresolved issue involves the sector's capacity to transform the 'availabilities' that suddenly emerge in disturbance-affected areas into harvests. During these episodes, a proportion of the affected wood volume is inevitably left in the forest, particularly in unmanaged stands, or because of market saturation leading to a fall in wood prices. Depending on the nature of the damage, a portion of the usable volume can be exploited in conventional ways (this is the case with windfalls, where the quality is maintained if they are processed quickly). However, other types of damage degrade the quality of the wood, and the usable volumes will then be used mainly as fuel wood or, possibly, as pulpwood (e.g. softwoods with bark beetle damage in the 'storms, bark beetles and fires' scenario).

Due to the scale of the severe events, the excess mortality is beyond the level of historical, documented events in France. The exploitation of these wood volumes is strongly dependent on market reactions (both internal and external) and on the sector's capacity to exploit and/or store this wood. While respecting the principles of the different management scenarios (e.g. reduced absorption capacity in the case of 'Extensification'), the percentages of the different shares (wood left in the forest to join dead wood/recovered lumber/recovered wood for pulp and energy) were set using 'expert opinion' (Table 7.1).

Table 7.1. Methods for valuing the volumes of excess mortality linked to the extreme events.

Scenario	Type of wood use		Drought		Fires	Insect
			Hardwood	Softwood	All species	Hardw
Intensification and Territorial Dynamics	Left in the forest		0%	0%	30%	30%
	Harvested & utilised	LW	According to uses derived from FFSM	0%	10% of the 70% harvested	Accordi to uses derivec from FF
		PW-EW		100%	90% of the 70% harvested	
Extensification	Left in the forest		0%	0%	60%	60%
	Harvested & utilised	LW	According to uses derived from FFSM	0%	0%	Accordi to uses derivec from FF
		PW-EW		100%	100%	

LW: lumber.
PW-EW: pulpwood and energy wood.

Due to the lack of detailed knowledge of the behaviour of economic actors following this type of disaster, no 'post-disturbance' adaptation of forestry management has been envisaged. Thus, the current stand types and current management practices have been retained by default (no stand conversion, no modification of post-disturbance silvicultural practices etc.).

Given the specific difficulties that they pose, the particular cases of the reforestation plan and poplar plantations have not been included in the analysis of these risks. Nevertheless, as the reforestation programmes would end at the time of the projected severe events (2025-2030), the volume of damage would be minimal, as the stock of standing trees potentially exposed to severe disturbances would be very small (approx. 3 m^3/ha on average over 3% of the forest area).

Consequences to the sector of the damage caused by severe disturbances

Each type of disturbance described above will have unique impacts on the dynamics of forests and the associated wood sectors, and these impacts could also vary depending on the management scenario and the severity of climate change (if the extent of the disturbance is directly related to climate change). Since biological invasions have not been specifically linked to climate change, neither in terms of initiation nor in terms of impacts, the consequences of this type of event was only be examined under the current climate. Their association with a worsening of climate change would result in a simple scale effect.

Moreover, in order to manage the size of this exercise, only the 'Extensification' and 'Territorial dynamics' management scenarios were used, for illustrative purposes. By combining the different severity options for the three severe disturbances and, where appropriate, the two climate options defined and discussed previously, eight situations per management scenario were simulated and analysed (Table 7.2).

Table 7.2. Summary of simulated extreme events for each of the 'Extensification' and 'Territorial Dynamics' scenarios (climate × severe disturbances).

Climate trajectory Severe disturbance	Current climate	RCP-8.5

Fires	Simulated	Simulated
Storms, bark beetles and fires	Simulated	Simulated
Biological invasion of softwoods Severe: all pines	Simulated	Not simulated
Biological invasion of softwoods Maritime pine only	Simulated	Not simulated
Biological invasion of hardwoods Severe: all oaks	Simulated	Not simulated
Biological invasion of hardwoods Only the common oak	Simulated	Not simulated

The damage caused by the fire outbreak occurring between 2026 and 2030 would double under RCP-8.5 compared to that under the current climate. The area affected would increase from 75,000 to 175,000 ha and the volume of additional mortality would increase from 15 to 36 Mm^3.

A cascade of ‘storms, bark beetles and fires would affect 9% of the surface area (700,000 ha severely, with the same amount of diffuse damage). In terms of volume, the damage would be the same for both climate options, and varies slightly between the two management scenarios (330 Mm^3 for ‘Extensification’ compared to 324 Mm^3 for ‘Territorial dynamics’). However, it should be noted that the almost identical amount of total damage between the climate options masks differences in the distribution of impacts, with considerable windfall in the current climate, but twice as much volume destroyed in the RCP-8.5 scenario due to the fires that follow the storm. This disaster would be approximately twice as severe as that caused by the Lothar and Martin storms of 1999.

Severe biotic disturbances affect the entire territory, and their severity depends on the number of and initial importance of the species affected: 120 Mm^3 if Maritime Pine alone is affected, about 350 Mm^3 if it affects all Pines or the common oak, and 800 Mm^3 if the three large oaks are affected, which is very considerable. Since the climate does not play a role in defining the disturbance, only the management scenarios vary in terms of the damage caused: the ‘Extensification’ scenario differs from ‘Territorial dynamics’ by only +5% damage. In terms of wood recovery by the sector, it is important to add that damage of biotic origin appears progressively over time and in a more or less diffuse manner across space, which makes it possible to prevent collateral damage and to manage the consequences in a ‘smoother’ manner than in previous cases.

In all three cases, the differences between the two simulated management scenarios remain modest, a result undoubtedly linked to the limited differentiation of circumstances between scenarios. This is due to the fact that the severe disturbances invariably erupt early, which allows stands to recover by 2050.

The post-event mechanisms that we have represented mainly concern the ecosystem. The feedback effect between basal area and recruitment causes a large increase in regeneration in damaged sub-domains. Those completely destroyed by the event (fires, core zone of the storm, etc.) are returned to production ten years later[35], with recruitment corresponding to that of new afforestation. Figure 7.4 shows that the loss of volume is only very gradually compensated for by greater regeneration.

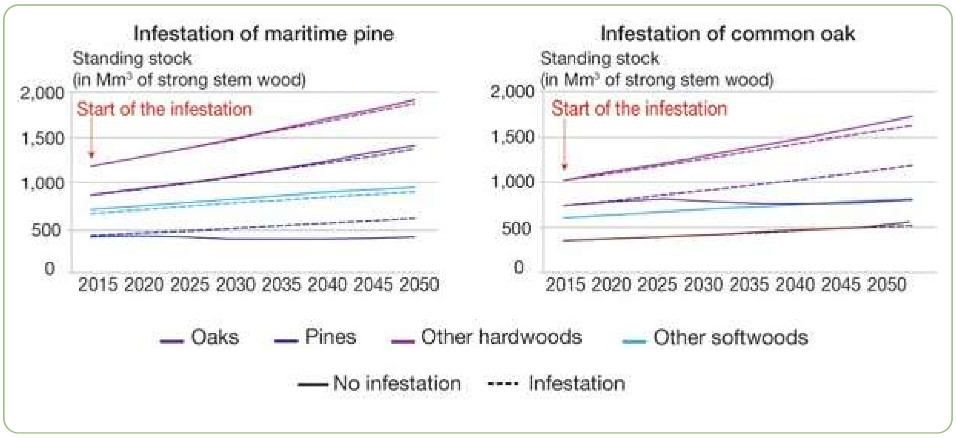

Figure 7.4. Changes in standing timber stock by species group, according to the type of biological invasion ('Territorial dynamics' scenario under the current climate).

Due to the lack of precise knowledge of the behaviour of stakeholders following this type of disaster, a minimum 'post-event' adaptation of silvicultural management has been assumed. Thus, current stand types and management practices are maintained (no stand conversion, no modification of post-event silvicultural methods), except in the case of biotic disasters for which we assumed that replanting would be done with accompanying species (mainly secondary hardwoods). In reality, such considerable damage would probably have an impact on silvicultural management with, in the case of ash dieback, a conversion of some stands or an adaptation of harvesting and management strategies. Hence, 2,214,000 ha (14% of French forests) for the common oak, 5,366,000 ha (34% of forests) for the 3 oaks, 1,195,000 ha (8% of forests) for the maritime pine and 2,772,000 ha (18% of forests) for the 5 pines could potentially be affected. These little-documented mechanisms, which are difficult to parameterise given current knowledge, have not been considered here.

The excess mortality was divided between an economically valued portion and a portion remaining in the ecosystem in the form of dead wood. These were set at arbitrary rates, depending on the scenario, in relation to the sector's capacity to absorb exceptional quantities of wood and/or sanitation felling. As seen in Table 7.1, the valued portion was set at 40% in the 'Extensification' scenario against 70% in 'Territorial dynamics', and leads to an increase in the harvest of the impacted species for industrial wood and energy wood before the resource is gradually depleted. These rates would benefit from further study, combining current expertise and economic analysis (wood prices, management levels).

Effects of the severe disturbances on the carbon balance of the forestry & wood sector

Regardless of the type and magnitude of the severe disturbance affecting forest dynamics, their effects reveal the same response patterns: the decline in annual carbon storage in standing timber, the significance of which depends on the disturbance, is initially at least partially offset by increased storage in dead wood and by substitution effects, which are driven by the increase in availability due to the disturbance. In addition to this mechanism, and particularly in the case of the 'Territorial dynamics' scenario, there is also significant storage in wood products. The detailed results of the effects of each of the projected severe disturbances on carbon storage in forests and wood products, as well as on substitution effects, are available in Roux *et al*. (2017, Annex 13). The impacts of these various events on the carbon balance of the sector will be discussed in detail here, based on the cumulative effects over the entire 2016-2050 period, and distinguishing between carbon storage in the forest ecosystem and substitution effects.

Effects of severe biotic disturbances

In the case of biological invasions, the species affected (whether oak or pine), as well as the severity of the attack, are crucial in determining the extent of the resulting damage and its effects on the carbon balance. In the case of pine trees being affected, the impact on the carbon balance over time varies little according to the management scenarios or the severity of the envisaged infestation. However, on a cumulative basis over the period 2016-2050, if the infestation only affected maritime pines, forest storage would decrease by less than 5% (Figure 7.5A) and avoided emissions would remain unchanged (Figure 7.5B). In addition, storage in wood products and substitution effects would both increase under the 'Territorial dynamics' management scenario, even though the carbon balance would still be dominated by storage in hardwood biomass.

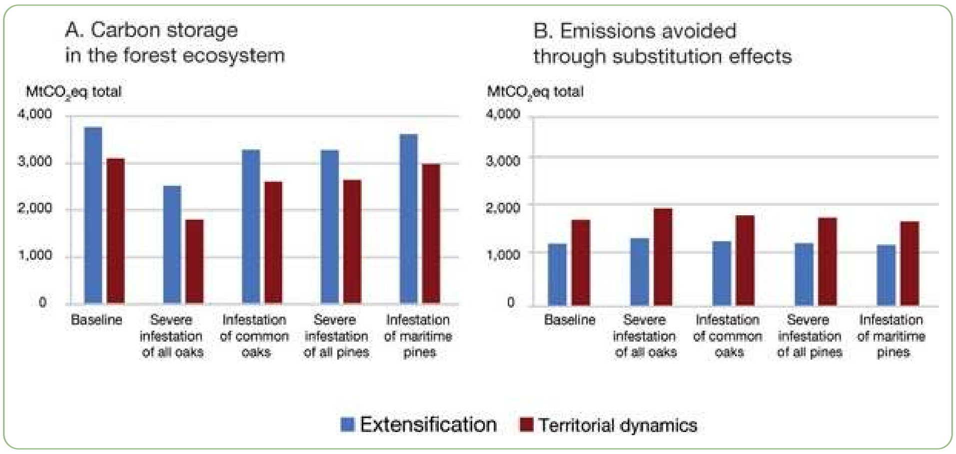

Figure 7.5. Cumulative carbon balance over the period 2016-2050 for the 'Extensification' and 'Territorial dynamics' management scenarios, in the event of biological invasions on oaks or pines, under the current climate ($MtCO_2eq$).

When oaks are affected, the impact on the different components of the carbon balance is much more significant, especially when all oak species are affected simultaneously (Figure 7.6).

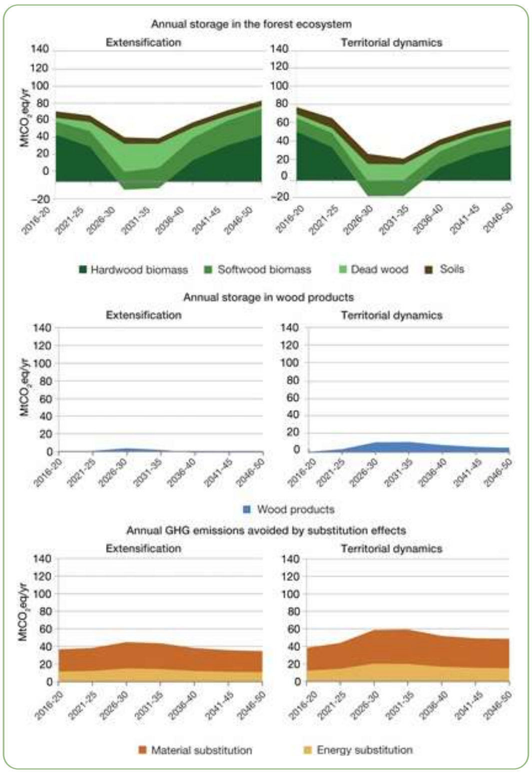

Figure 7.6. Impact of a severe biological infestation (affecting all oaks) on the various components of the carbon balance, under the 'Extensification' and 'Territorial dynamics' scenarios, and under current climatic conditions ($MtCO_2eq$/year).

Oak losses due to mortality are sufficient to slow down the storage rate or even to switch to a reduction of hardwood biomass. Thus, annual carbon storage in hardwood biomass decreases sharply from 2021-2025 on, and even becomes negative over the following two periods (2026-2030 and 2031-2035). In this case, all of the other drivers which are triggered by the disturbance, such as dead wood, storage in products and substitution effects, compensate for the significant loss of oaks. However, the additional storage in dead wood is not sufficient to maintain annual storage in forests.

Thus, taken as a whole over the period 2015-2050, the cumulative storage in the forest ecosystem, when the biological invasion affects all oak species (under the current climate), decreases by 33% under the ‘Extensification’ scenario and by 42% under ‘Territorial dynamics’ (Figure 7.5A). At the same time, carbon storage in wood products and emissions avoided by substitution effects, which increased sharply during the periods during which the events occurred, did not increase sufficiently to compensate for all losses related to forest destocking: +9% cumulative substitution from 2016-2050 under the ‘Extensification’ scenario and +12% under the ‘Territorial Dynamics’ scenario (Figure 7.5B).

Effects of severe abiotic disturbances and the cascade of effects (fires and storms)

At the national level, the impact of a ‘drought then fires’ disturbance on the carbon balance would be absorbed, and thus pass almost unnoticed amidst the variability between years. Under current climatic conditions, the growth of carbon storage in forests would simply slow down. In the event of more severe climate degradation (RCP-8.5), forest damage would be more significant, with the area burned 2.4 times that under the current climate scenario. However, the overall impact remains limited, as the other segments of the sector play their full role as ‘shock absorbers’. Cumulative forest storage over the entire 2016-2050 period is less than 1% below the no-disturbance scenario in all cases except under ‘Territorial dynamics’ and RCP-8.5, where the deviation from the no-disturbance situation is 3% (Figure 7.7A). In this case, a slight increase in substitution effects compensates for this slight loss (Figure 7.7B).

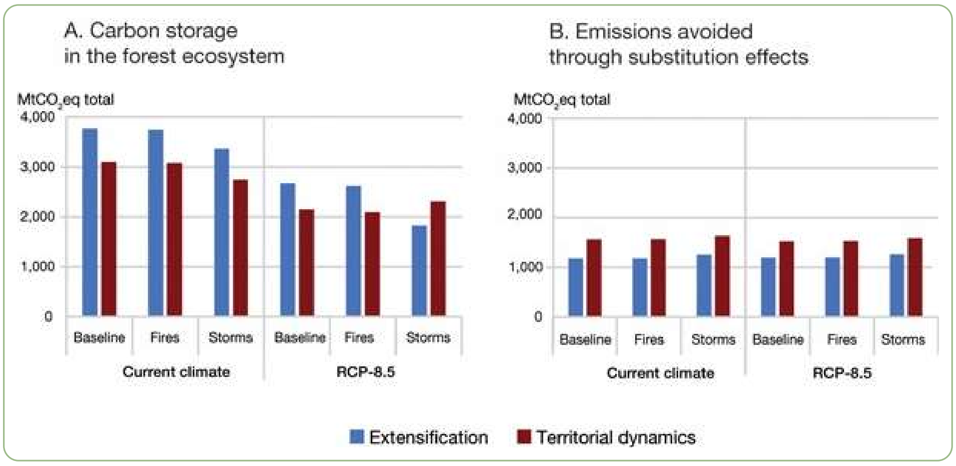

Figure 7.7. Cumulative carbon balance ($MtCO_2eq$) over the period 2016-2050 for the ‘Extensification’ and ‘Territorial dynamics’ management scenarios, in the event of abiotic disturbance (fires and storms), according to climate trajectory (current climate and RCP-8.5).

However, it should be recalled that, in order to simplify the analyses, only one ‘drought then fires’ disturbance was positioned during the study period. A more likely scenario would see a recurrence of such events with each significant drought. In particular, if the effects of climate change worsen (RCP-8.5), a more extreme climate with a succession of dry years, such as the 2003-2006 series, would be expected. Each event would certainly be of a smaller scale than the one simulated here, but the cumulative effects could be far greater. Recurrences could also have a destabilizing effect on the forestry & wood sector, which could lead to an aversion to undertaking projects, thus crippling initiatives.

Conversely, following a storm and its complications (a cascade of storm, bark beetles, and fires), storage in biomass (both hardwood and softwood) would be sharply reduced and, in some cases, even cancelled out during the five years of the disturbance, as was the case of the Lothar and Martin storms of 1999. Nevertheless, immediate offsets would occur through the accumulation of dead wood and carbon storage in wood products, amplified by an increase in substitution benefits.

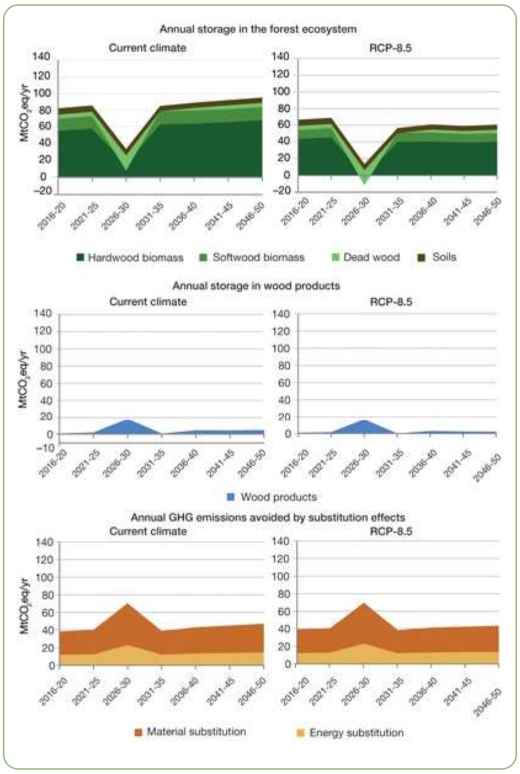

Figure 7.8. Impact of a storm followed by bark beetle outbreaks and fires on the components of the carbon balance, under the 'Territorial dynamics' scenario, and under both current climate and RCP-8.5 ($MtCO_2eq$/year).

Thus, for example, under the 'Territorial dynamics' scenario with current climatic conditions, storage in forests falls sharply from nearly 84 $MtCO_2eq$/year during the period 2021-2025 to 33 $MtCO_2eq$/year in 2026-2030, after the passage of the storm. The negative impact on forest biomass is somewhat offset, in the forest ecosystem itself, by an excess of dead wood that retains some of the forest's carbon. At the same time, due to the significant supply of wood for processing, carbon storage in wood products and substitution effects increase sharply as a result of the disturbance: by 75% for GHG emissions avoided and by a factor of 10 for product storage (Figure 7.8). The shock is even more severe under the worsening climate option (RCP-8.5), whereby carbon destocking in forest biomass occurs. However, at the same time, dead wood storage almost quadruples, and the substitution effects and storage in wood products both increase dramatically.

Overall, under current climatic conditions, compensation is almost total under both of the management scenarios considered, with annual storage levels for the pre-disturbance (2021-2025) and disturbed (2026-2030) periods remaining broadly identical. However, a downward trend would occur if the climate followed the RCP-8.5 trajectory, but it would be limited to approximately -10%. With subsequent periods returning to annual storage growth levels or substitution effects close to pre-disturbance levels, the cumulative carbon balance over the entire 2016-2050 period would be 5-6% lower than it would be without the storm and its aftermath (Figures 7.7A and 7.7B).

Conclusion of Part III

Although these factors are very rarely included in this type of study, as expected, a more pronounced worsening of the climate and the major disturbances that could affect forest dynamics would impact the national carbon balance in very contrasting ways. This would depend on the degree of climate change deterioration and the nature of the disturbances, the affected trees, and the severity and dynamics of the phenomenon.

The worsening of the effects of climate change as per the IPCC's RCP-8.5 trajectory would on its own significantly reduce the carbon balance of the French sector, regardless of the management scenario adopted. The capacity to store carbon in

French forest biomass would be impacted in the long term, possibly decreasing by 27 to 30% as compared to the levels if current climatic conditions could be maintained, bearing in mind that they have already deteriorated. However, the impacts of this reduction in the sector's carbon balance could be cushioned through substitution effects, as the proposed management scenarios would allow an increase, even if moderate, in harvests and in the use of wood products. The sustainability of additional wood harvests, even under conditions of declining stocks, is not compromised at the broader scale. On the other hand, under these conditions, special attention will be needed at the local level to ensure that the stands that are currently the most exploited or the most sensitive to climatic effects do not see their levels of extraction reaching or even exceeding sustainability thresholds.

A fire season even twice as severe as 2003 would lead to a very low national impact. In the other hand, a disaster triggered by a storm twice as severe as Lothar-Martin (in volume of windfall and broken stems), with complications due to bark beetle outbreaks and fires, would have an impact of -15% on the national carbon balance, which would then be corrected within about twenty years. An invasive species outbreak would have more widespread consequences throughout the period, the most severe outbreaks being those affecting all oaks, which could kill or weaken up to 800 Mm^3 cumulatively over 20-30 years (up to -20% of the carbon balance). Given their preponderance in the French forest resource base, the carbon balance is generally more sensitive to events that principally affect hardwoods. In addition, recovery after a disturbance would be slower under the RCP-8.5 climate projection than under current conditions for all of the components that contribute to the carbon balance (dead wood, wood products and substitution).

We cannot clearly distinguish between the two management scenarios simulated here ('Extensification' and 'Territorial dynamics') in the face of major disturbances, even a very severe one. This may be due to the fact that the timing of the damage was arbitrarily focused on the beginning of the simulated period and without repetition of the severe disturbance, in order to observe the consequences up to 2050. Thus, the use/management scenarios do not yet have sufficient time to show a clear divergence with respect to resource characteristics.

The economic and social dimensions of the management of these severe disturbances were dealt with very briefly here. On the one hand, we could only partially simulate the post-disturbance dynamics of forests (especially those undergoing regeneration). On the other hand, we assumed that the proportion of damage valued in terms of products would be 40% under the 'Extensification' scenario and 70% under 'Territorial dynamics', without being fully able to assess the realism of such assumptions, given that the damage envisaged is unprecedented in magnitude.

These severe disturbances are likely to weaken, cancel out or even reverse the rate of carbon accumulation in forest biomass for several years. Provided that stands and their managers have the capacity to respond at the required scale, this impact should remain below 15 years (which is nonetheless important). Climate change, which weakens growth, increases mortality and could increase the frequency and severity of disease outbreaks, indeed constitutes an important risk factor, particularly with respect to strategies that focus on carbon storage in forests.

Given the magnitude (in hectares and millions of cubic metres per year) of the severe disturbances under investigation, current crisis prevention and preparedness practices (Gauquelin *et al.*, 2010) may not yet be at a sufficient scale. If only to increase the resilience of their management systems, forestry practitioners would benefit from strengthening their training to respond to such events.

The integration of major biotic and abiotic risks, which can also be combined, is a highly innovative approach for this type of study. In addition to the need to acquire data that is specifically geared to calculating vulnerability indices, more in-depth research is required to integrate these events more dynamically into resource models. This includes the incorporation of changing vulnerabilities of stands over time, and increased our knowledge to allow the inclusion of post-disturbance aspects (economic and social factors), etc.

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23 Drias portal: www.drias-climat.fr.

24 http://www.drias-climat.fr.

25 More details in Roux *et al.* (2017, Annex 8).

26 ICP Forest Level I consists of a Europe-wide systematic network of representative plots of forest ecosystems. It is periodically used to produce a spatial overview of variations in forest conditions in relation to anthropogenic and natural stressors, especially air pollution.

27 The locations of water deficit zones in metropolitan France are derived from the water balance results of

the GO+ functional model, associated with regional climate scenarios.

28 Edaphic drought is triggered by climatic forcing, with high interannual variability already occurring in the current climate. It should be remembered that the climate scenarios are statistical models, and that the precise location in time is purely random; thus, the year of maximum drought calculated by the GO+ model per climate scenario lies within a time window (near future or far future, here in a thirteen year time frame), but has no specific date significance as such.

29 The FWI is a composite fire danger index integrating several primary indicators. It ultimately combines an initial fire spread rate with the quantities of fuel available (Van Wagner, 1987). It integrates, among other things, the consequences of drought conditions on the availability of combustible vegetation for fire. It is solely based on meteorological parameters, which makes it possible to apply to past observed meteorological data or future simulated data.

30 The Safran dataset covers France at a resolution of 8 km on an extended Lambert-II projection. They are produced by Météo France (Centre national de recherches météorologiques, CNRM).

31 Details of these methods can be found in Roux *et al*. (2017, Annex 9, pp. 3-4).

32 Details of these methods can be found in Roux *et al.* (2017, Annex 10, p. 5-6).

33 More information in Roux *et al.* (2017, Annex 10, p. 5-8).

34 The basal area corresponds to the cross-sectional area of a tree measured at 1.30 m from the ground. This measure quantifies the competition between trees in a forest stand.

35 This ten-year period is intended to take into account the difficult terrain conditions after disturbance (obstruction due to windfalls, etc.) and the minimum diameter of the forest inventory, which means that only trees over 7.5 cm in diameter are counted.

General conclusions

Originality of this approach

The approach adopted in the course of this study was aimed at analysing the mechanisms that could be activated in the coming decades to improve the already significant contribution of the French forestry & wood sector to climate change mitigation. It was intended to be as comprehensive as possible and, as a result, drew on a broad range of multidisciplinary expertise to address the multiple aspects of the topic. It thus contains several original approaches that have seen little use in existing research on this issue (Valade *et al.*, 2018; Nabuurs *et al.*, 2015; Lundmark *et al.*, 2014; Pingoud *et al.*, 2010; Schwarzbauer et Stern, 2010; Thürig et Kaufmann, 2010). These include analyses at the national scale, the simultaneous consideration of forest dynamics, sector dynamics and economic dynamics through to 2050, the integration of the effects of climate change and severe disturbances affecting forests in France, etc.

By focusing on the 2050 time horizon, which is near in the case of forest dynamics but distant for economic, social and technological dynamics, we have chosen to simulate the effects on the carbon balance of three coherent and contrasting forest management scenarios. This prospective approach, which is rarely used in the forestry sector[36], has been expanded, on the one hand, by the development of a realistic reforestation plan adapted to the constraints of French forests and, on the other hand, by the implementation of a simulation methodology that integrates three specific models:

– the IGN resource model, which is calibrated to simulate forest dynamics over short time horizons, has been pushed to its limits. This has shown that one of the keys to improving carbon accounting over longer time frames lies in the models' capacity to represent forest stand behaviour at very different densities over very long periods;

– an economic model of the sector to better understand the possible harvesting dynamics according to market capacities. Beyond the economic results that emerge, this analysis highlights that, if the objective is to increase the use of wood products, it can only be considered if there are fundamental changes in, firstly, consumer preferences for wood products and secondly, industries downstream of the sector that must develop the capacity to process and market the most ethical products;

– IGN modelling based on statistical and demographic processes, with, in addition, consideration of climate change effects, which required the use of modelling principles based on biological processes. The articulation between these two types of models, which has made it possible in this case to simulate the effects of climate change on forest dynamics, suggests the need for further work in this direction to better understand the ways in which forests respond to unfamiliar, and therefore unobserved, conditions.

In a similar vein, it was considered necessary, in order to explore changes to French forests and their contribution to climate change mitigation, to consider severe biotic or abiotic disturbances (crises) that could significantly change the terms of the trade-off between storage in forests and storage and substitution in the rest of the sector. This approach, which has never been attempted at this scale, highlights the importance but also the difficulties of documenting and simulating the multitude of possible risks and cascading risks.

Offsets between components of the carbon balance differentiate the forest management strategies

Despite the uncertainties and limitations of available knowledge and tools, this analysis shows that the overall carbon balance of the forestry & wood sector involves deferrals and offsets (between different stocks, and between stocks and substitution) that ensure a certain stability. Even if a particular component (for example, the biomass of a group of species affected by a very severe disease outbreak) may experience temporary negative balance phases (i.e. net carbon loss), the overall balance over this period remains positive. Its magnitude (100 to 170 $MtCO_2eq$/year) makes French forests and the French forestry & wood sector major contributors to the national greenhouse gas balance.

This is largely the result of the general process of expansion of the surface area of forests in mainland France and the build-up of standing timber within these forests. In fact, beyond the increase in surface area, each hectare of forest, on average, continues to accumulate volume under the combined effect of the maturation of ‘young’ forest areas (created over the last fifty years) and a low level of active management on large areas of mainly private or communal land. These phenomena exhibit a high inertia over periods of several decades, which explains why even the very strong disturbances that we have simulated, whether anthropogenic or natural, are completely or very largely absorbed during the 2015-2050 period. However, it should not be assumed that this strong overall inertia and resilience of the forest ecosystems are intrinsic properties of the ecosystem. They probably also reflect a unique ecological, industrial and social context:

– after an ‘historical minimum’ at the beginning of the 19th century, the French metropolitan forests are still in the process of being ‘re-established’, including their ‘soil’ component, which currently stores carbon at a rate close to 4 ‰;
– the uses for which forests were once heavily exploited have been replaced by fossil fuels, concrete and metals;
– the rapid urbanization of society has led to a certain geographical and cultural disconnection of the population from the forest as a productive space, while the forest is gradually being seen as a space of recreation, nature, biodiversity and other non-market services.

This historical situation, which today results in a highly positive carbon balance in forests and the forestry & wood sector, could change in the future, as could the carbon balance: as a backdrop, there is concern that rapid climate deterioration, particularly under the IPCC’s worst-case scenarios, could negatively impact forest productivity and increase tree mortality. In addition, the emergence of severe disease outbreaks is one of the most worrying and emerging symptoms of climate change, both in terms of their impacts on forest cover and in terms of potential disruption and transformation in the socio-economic realm.

Finally, the forestry & wood sector is one of the main sources for the bioeconomy, which is emerging in order to substitute bio-sourced products for products derived from fossil resources (Roy, 2006). This encompasses the issues that we have sought to address in this study.

The various analyses in this study highlight and confirm that the different drivers and sub-sectors (i.e. storage in biomass, dead wood and soils, storage in wood products, and emissions avoided by substituting wood for competing energy- or material-producing processes) play complementary roles in the overall impact of the forestry & wood sector on the national carbon balance. For example, if wood exploitation peaks due to the rapid harvest of windfalls caused by storms, the slowdown in biomass storage is largely offset by phenomena acting in the opposite direction (immediate benefit in terms of emissions avoided by the use of wood and/or massive storage in dead wood in the case of damaged wood that foresters cannot save). This compensation mechanism between storage in forests and substitution in the sector highlights the importance of having as complete a representation as possible of the problem, whether ecological, industrial, or socio-economic (Petersen and Solberg, 2005). The sole consideration of forest stocks, on which attention is generally focused, can provide a biased view of the impact of forests and the forestry & wood sector.

Seen from this perspective, the three forest management strategies envisaged here can, despite the intense debates they are currently generating, be viewed as difficult to differentiate in terms of the cumulative carbon balance up to 2050. Indeed, the benefits that a strategy of extensification of harvesting would have on carbon storage in forest biomass could be very strongly reduced if forest growth dynamics no longer follow the same trends as today, and instead slow down under the effect of ageing stands and/or worsening effects of climate change. Conversely, the drawbacks of strategies to intensify harvesting, either by maintaining current harvesting rates (‘Territorial dynamics’ scenario) or by increasing them (‘Intensification with (or without) a reforestation plan’ scenario), could be offset by developing and increasing the use of wood products with strong substitution effects. The economic analysis nevertheless highlights that such a strategy can only be envisaged at the price of a realignment and (re)development of French industrial wood processing structures, which in turn requires changes to public policy.

We have also attempted to design a reforestation plan to create new, highly-productive and easily mobilized wood resources to supply the bioeconomy. As in the case of poplar plantations that are presently cultivated, the concept involves devoting a small proportion of the forest area to silviculture where the production objective is assumed and clearly stated (which does not prevent these stands from, as in the case with poplar plantations, providing many other ecosystem services). The species and varieties proposed were specified (supply of plants, technical procedures, performance, and known risks) and their potential identified by major ecological regions. The impact of such a plan on the national carbon balance would nevertheless only start to become significant after 2050, and thus respond to the anticipated scarcity of certain stocks (e.g. Douglas fir beyond 2030). To go further, it would be useful to place this plan among the different options for adapting to climate change, particularly in terms of plant breeding, the dissemination of improved varieties and the development of seed orchards (Merkle and Cunningham, 2011; Nijnik *et al.*, 2013). Maritime pine and Douglas fir are thus included as key species, both for adaptation and to increase productivity.

Different uncertainties can be reduced to differing extents

By examining the technical coefficients used to conduct carbon accounting for the entire sector, we have highlighted the multiple uncertainties inherent in this type of approach. These uncertainties are of various types:

- limitations in the current versions of existing models when they are used for longer horizons (e.g. MARGOT does not take into account stand density effects, FFSM contains no investment module, limited numbers of modelled species, and limits to environmental variability in the GO+ process model) ;
- difficulties in linking models (demographic and process-based, in particular);
- range of variability of the technical coefficients (substitution, half-lives, etc.) and factors influencing their possible changes over time.

While some of the above uncertainties can probably be reduced by improvements in measurement and modelling tools, uncertainties relating to the assessment of substitution effects, particularly for wood materials, must be considered separately. The very wide variation in coefficients found in the literature can be explained by the diversity of wood products and their competitors, and by the many different technologies and energy contexts to be considered. A rigorous evaluation of this sub-sector requires a more detailed breakdown of the sector and its products, and a deeper analysis of the methods used to evaluate the emissions of the various competing production systems used as a reference. Only then can assumptions be made about their evolution, taking into account possible technological developments that would alter the avoided emission differential between wood products and competing products.

Carbon balances are affected by worsening climate change and severe disturbances

The effect of a worsening of climate change along an RCP-8.5 emissions trajectory can be summarized as a general slowdown in growth and a sharp increase in mortality.

By 2050, however, such conditions appear to be compatible with a sharp increase in the harvesting levels, as envisaged in the 'Intensification' scenario, in comparison with the current harvest, which makes it possible, in terms of its contribution to mitigation, to absorb the decline in forest storage capacity. Nevertheless, the assumptions used are rather drastic with regard to the impact of climate on forest dynamics. In this manner, the development of hardwood forests has been constrained by climatic forcings calibrated for beech, a species that is more sensitive to drought than the majority of hardwood species. A more specific calibration would certainly make it possible to better characterise these impacts, differentiated by the major species (western oak forests, lowland pine forests, mountain or lowland beech forests, fir forests, spruce forests etc.) and thus assist in prioritising climate change adaptation measures.

With regard to the severe disturbances, we have simulated very damaging scenarios. On the one hand, we have sought to obtain a considerably greater amount of damage than recent historical precedents (Lothar and Martin in 1999, Klaus in 2009, drought in 2003, etc. On the other hand, we have deliberately put the simulated system at risk by choosing ecologically and industrially sensitive targets, such as a storm track across the country that impacts large areas of spruce and quality hardwood, or severe biotic disturbances that specifically affect groups of species with high potential for climate change adaptation, such as oaks and pines. Damage recovery rates (recovery of damaged wood) are 40% under the 'Extensification' scenario and 70% under the 'Territorial dynamics' scenario. Under these conditions, the impact of the severe disturbances penalizes biomass storage more strongly and for longer in the event of a biotic disturbance than in the event of a storm, but is eventually offset by 2050. We do not claim to have captured every possible impact of such events here. In our simulations, severe abiotic disturbances occur only once between 2016 and 2050, but their repetition would probably worsen the consequences. In addition, the product exploitation process at the time of the event were modelled as being very straightforward. However, it is more likely that we would be dealing with a destabilization of industries deigned for slow resource processing, and profound socio-economic impacts partly related to the degradation of the corresponding landscapes.

One of the distinctive features of the inclusion of severe disturbances is that, from the outset, a multi-risk approach was adopted, which considers the interactions between risks. This calls for the establishment of a national network of academic and operational stakeholders on biotic and abiotic risks in forests in order to further the analysis.

Further scientific and methodological research

In view of the relative contributions of the different mechanisms, it is clear that net storage in products remains, in any case, of low importance compared to other mechanisms. Nevertheless, it should be kept in mind that we have not fully characterised the consequences of the use of by-products of the wood production process, nor the strong prolongation of the lifespan of these products. However, as desirable as such progress may appear, it is unclear whether the increase in the stock of wood captured in the economic sphere will, in itself, become a major carbon sink. Beyond the question of processing yields and product life, it is during the transition phase from a society that consumes a substantial amount of fossil resources to a society that uses wood on a massive scale that storage can play an important role, although this would no longer be the case under steady state conditions.

Forest soils are currently in a non-stationary state, being characterised by an annual carbon accumulation rate close to 4 ‰. We have retained a fixed value of 7 million tonnes of CO_2eq per year, which may be less than the actual value. It would be of considerable value to develop specific models to illustrate how soil carbon dynamics will respond to changes in climate and management practices, in terms of extensification, adaptation to climate change and the development of innovative technical guidelines to supply the bioeconomy.

The inclusion of the dead wood component has a significant impact on the overall assessment of the scenarios. In the event of a storm followed by a cascade of other damage (bark beetles, fires) or during severe biotic disturbances lasting twenty years, such as the pine beetle outbreak in North America (we simulated an emerging disease that would affect the most important oaks), significant accumulation would occur in the dead wood component, which acts as an important buffer in the sector's overall carbon balance. This buffer role is particularly important, as the rate of effective utilization of damaged wood is low (in the 'Extensification' scenario, we have assumed that 60% of the wood remains in the forest).

From a methodological perspective, the study revealed a fundamental conclusion. To improve the suitability of the IGN MARGOT model when simulations are required beyond the short or medium term (twenty years) and/or to consider a wide range of management/utilisation strategies, the introduction of density-dependent rules that control recruitment rates, growth and mortality give the projections more realistic dynamic behaviours (non-amplification of disturbances, saturation of production or stimulation of individual growth at both extremes of relative stand density), the consequences of which we have seen via the management strategies.

Similarly, the use of a model such as FFSM, which was built to answer research questions, can be hazardous for studies with a direct operational focus. FFSM has been deployed as is for the needs of this study, which are significantly different from the research issues that gave rise to the tool. Thus, it does not allow us to answer all of the questions raised by the study, particularly in terms of the representativeness of the economic stakeholders in the sector. Consequently, for uses over distant horizons and under somewhat radical assumptions regarding change, FFSM suffers, like all economic models, from its lack of flexibility in terms of price elasticity, particularly in terms of demand, which can reflect changes in consumer preferences. Moreover, the inclusion within the model of the investment behaviour of downstream industries is important to consider. It would be difficult to implement, but all the more crucial as it involves analysing the sector's capacity for change, with a view to increasing the capacity to harvest wood and market wood products. On this issue, a useful improvement would be to distinguish the behaviour of consumers of secondary processed products (now aggregated in the demand functions of the downstream subsector) as well as the nature of forest managers/owners (by distinguishing between state-owned, communal, small private and large private properties), all of which will react differently to the same supply drivers[37].

The combining of models, as explored in this study, has promoted dialogue between different scientific communities, leading them to increase the transparency of their methods and assumptions and enhancing each approach through interaction with the others. We found that, regarding the interface between the resource model and the process model, one improvement might consist of increasing the range of available parameters, which would be a challenge given that our country has at least a dozen important forest species. The interface between the resource model and the economic model of the national sector is less operational, and we have noted, in particular, a need to better anticipate trajectories in which stakeholders strongly adapt their behaviour.

Beyond the carbon balance, other services provided by the forestry & wood sector should also be considered.

The rationale behind policy choices relating to forests and the forestry & wood sector is based on multiple criteria. The carbon balance of the sector, while an important criterion, must be weighed against other considerations:

– the degree of vulnerability, resilience and reversibility of ecosystems and of the management applied (or not) to them: thus, a comparison of the three management scenarios shows us that, for similar overall carbon balance levels, the relative contribution of storage and substitution effects can vary greatly. However, carbon stocks, particularly those in biomass, are very sensitive to disturbances, while the benefits of substitution are permanent;

– policies that focus more on substitution than on accumulation in the forest are aimed at outcomes other than carbon (innovation, industrial activity, employment, regional prosperity, trade balance;

– in the broader energy policy debate (where issues of availability, intermittency, supply-demand balance and storage are also important), wood can be viewed as stored solar energy, easily deployable and therefore flexible. Maintaining the national wood stock at an intermediate level of density (neither too low nor too high) further enhances this flexibility by allowing for both upward and downward adjustments;

– forests provide a number of ecosystem services that are highly valued by society (areas for recreation, air and water quality, scenery, biodiversity, etc.). Although it is neither obvious nor promoted by stakeholders, the fact that forests are managed contributes significantly to making some of these services readily available, and to ensuring some stability in their provision, especially in times of severe disturbance. A more complete explanation of these links between management and the quality of ecosystem services would certainly help to improve the social acceptability of changes to management practices, which now seem unavoidable (Millar *et al.*, 2007) in the context of climate change.

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36 A notable exception in this respect is an earlier study conducted by INRA (Sebillotte *et al.*, 1998).

37 Explanatory variables other than the price and change in the resource and/or different levels of elasticity

Annex
Determination of the areas to be reforested under the ‘Intensification’ scenario reforestation plan

The ‘Intensification of harvesting’ scenario was coupled with a reforestation plan of 500,000 ha over ten years in order to gradually increase the stock of wood-material products. Beyond the choice of species and their distribution, the development of this reforestation plan required the identification of areas where it could be implemented, along with the species to be planted in these areas.

Choice of areas to be included in a reforestation plan

Identifying areas with potential for reforestation

In order to define and locate potential areas for reforestation within the framework of the 116 forest classes, defined by the IGN to describe French forests (Colin and Thivolle-Cazat, 2016), an identification key was proposed and implemented on the basis of the IGN’s descriptive data on the resource.

Initially, exclusion criteria were identified in order to retain only the areas ‘eligible’ for reforestation in each of the 116 classes. These criteria address regulatory, ecological or technical aspects, all of which aim to encourage the establishment of plantations that are easy to establish, productive and easily exploitable. These criteria are detailed below. This approach has been applied separately for ‘non-poplar’ stands and poplar plantations.

‘Non-poplar’ stands (including plantations)

The total surface area of the 116 IGN classes (excluding poplar plantations) totals 16,620,900 ha. The following criteria for the exclusion of forest areas were applied to this total area. The following types of areas were excluded:

– forests not available for wood production, including small groves, difficult to access areas, protected areas or areas reserved for leisure activities, and exploited areas that already contain a reforestation project;
– areas with wood production issues, including ZNIEFF I (Natural Areas of Ecological, Faunistic and Floristic Interest), Natura 2000 areas, and areas with a protective function and military land;
– areas with limiting ecological factors, including areas with a minimum useful reserve of less than 70 mm, those at an altitude of more than 1200 m and areas with permanently clogged soil;
– areas with economic factors relating to exploitability, such as areas with a slope of more than 30%, areas with a skidding distance of more than 500 m and areas where there is no possibility of creating tracks.

After applying these exclusion criteria to the total extent of the forests identified by IGN, we determined the potentially reforestable area. Covering 4,516,854 ha, this represents 27% of the total surface area across the 116 forest classes.

Poplar plantation areas

Poplar plantations cover a total area of 179,000 hectares, according to IGN. The criteria for excluding poplar groves were then applied to this total area. The following types of areas were excluded:

– those with wood production issues. ZNIEFF I, Natura 2000 areas, areas with a protective function and military land;
– regarding current maintenance of poplar plantations. As the criteria used for stands ‘excluding poplar stands’ were irrelevant, we decided to retain the poplar groves classified as ‘not maintained’ on the basis that their productivity could be increased with adequate maintenance.

After applying these exclusion criteria, we were able to determine the potential reforestation area for poplar plantations, which amounts to 42,900 ha.

Selection of priority zones within areas with reforestation potential

Among the areas with reforestation ‘potential’ as described above, priority zones for reforestation were selected on the basis of the forest classes defined by IGN. The choice of classes that could be regarded as priorities for the reforestation plan followed a five-step process.

Step 1. Classes within the priority GRECOs: GRECOs A, B, G, F (très grand ouest de la France – ‘the west and centre-west of France’)

Efforts have focused on these GRECOs (Grand Ouest cristallin et océanique, Centre Nord Semi-Océanique, Sud-Ouest Océanique and Massif Central), as they are generally considered to be suitable for productive reforestation and suffer from few ecological or technical constraints. Replacement with different species can significantly improve productivity in these areas.

We added the already existing plantations to the areas already excluded due to the above-mentioned criteria, as we considered these plantations to be productive.

For the remaining areas, we selected the classes for which the current harvest rate was less than or equal to 30%, assuming that these low harvests were indicative of low stand management intensity. Other classes were excluded on the basis of the ‘value’ of the existing stands.

Some classes meeting the eligibility criteria described so far were not selected for various reasons related to the main species within the class:

– pubescent oak stands are invariably located on the most difficult sites, and it would be complex to replace them with a highly productive species;

– stands of valuable hardwoods (valuable species) and black locust (already very productive).

The total area of the IGN classes within GRECOs A, B, G and F is 945,916 ha. The seven classes selected for reforestation out of the total area of these GRECO classes cover 396,425 ha of potentially reforestable land. The vast majority of these are privately owned forests and are composed, according to IGN, of ‘other hardwoods’.

Step 2. Classes within secondary GRECOs: GRECO C, D, E

In this second stage, we extended the search to GRECO C, D and E ecoregions (Grand Est semi-continental, Jura and Vosges) using the same selection criteria as for the previous GRECOs, in particular by excluding plantations and selecting classes with a harvest rate of 30% or less.

Some classes meeting the eligibility criteria described so far were not selected for various reasons related to the main species within the class. For example, beech stands, which are particularly important in these GRECOs, were not retained.

The total area of the IGN classes within GRECOs C, D and E is 341,295 hectares. The three classes selected for reforestation out of the total area of these GRECO classes cover 96,434 ha of potentially reforestable land. The vast majority of these are privately owned forests and their main species is ‘other hardwoods’.

Step 3. Classes corresponding to stands that are at a silvicultural impasse (including plantations)

In this third phase, we extended the search to classes corresponding to stands made up of species facing significant growth declines, which could relate to attacks by emerging pathogens (ash, Corsican pine) or to problems of ageing stock (chestnut). For this reason, the ash and Corsican pine plantations were added to selected classes, and the filter on the harvest rate was not applied.

Regarding ash, only plantations were selected from GRECOs A and B, whereas all ash stands (stands and plantations) were retained from GRECO C. For Corsican pine, the selected classes (including plantations) are located in GRECOs A and B. Finally, the selected chestnut stands are located in Greco F, G (western zone) and I.

The total area of the IGN classes corresponding to the stands (including plantations) of ash, Corsican pine and chestnut totals 479,954 ha. These four selected classes are only found in private forests, the principal species are ash, Corsican pine and chestnut, and they cover 262,759 ha of potentially reforestable land.

Step 4. Classes within GRECO J (cedar in the Mediterranean region)

In the Mediterranean region, we considered that cedar could improve the productivity of forests on the best land.

The total area of the IGN classes corresponding to GRECO J (excluding plantations) is 137,347 ha. Only two of these classes were selected, the main species of which is (according to IGN) ‘other softwoods’ and have a low harvest rate. Within these two classes, 7,942 ha are potentially reforestable.

Step 5. Poplars

As indicated in Chapter 6, across all GRECOs, the ‘unmaintained’ poplar groves that could be reforested amount to 42,900 ha of potentially reforestable land.

At the completion of these five steps, 806,460 ha of land was estimated to be potentially reforestable. In order to ‘meet’ the objective of 500,000 ha of reforestation, we applied a ‘reforestation rate’ varying from 40% to 90%, depending on the geographical area and stand type (Table A.1).

– For priority GRECOs: between 70 and 90%, except for the common ash class, which covers a large surface area in GRECO B, and for which we have chosen 40%.
– For secondary GRECOs: approximately 50%.
– For stands in a state of silvicultural impasse: approximately 40% for common ash, approximately 75% for Corsican pine and 50% for chestnut.
– For Greco J and cedar in the Mediterranean region: approximately 80%.
– For unmaintained poplar groves: approximately 50%.

Table A.1. Summary of the areas (ha) selected at each selection stage, and the GRECOs or stands concerned.

Step	Number of classes	Total area of the classes	Potentially reforestable area	Reforestable area / total area (%)	Area selected for the 500,000 ha project
Priority GRECOs A, B, F and G	7	945,916	396,425	42	286,000
Secondary GRECOs C, D and E	3	341,295	96,434	28	53,000
Stands at a silvicultural impasse	4	479,954	262,759	55	135,000
GRECO J (Mediterranean region)	2	137,347	7,942	6	6,500
Poplar plantations	n.a.	179,000	42,900	24	20,000
Total		2,083,512	806,460	39	500,500

Allocation of species to classes

After having chosen the areas to be reforested from among the 116 IGN classes, we distributed the target species throughout these classes based on the pedoclimatic adaptation of each species. The details of this distribution are presented in Table A.2. The principal focus is on the mostly hardwood stands within the priority GRECOs (the greater western half of France) and the stands experiencing a silvicultural impasse (84%). Significant additional contributions come from the secondary GRECOs (11%), while the Mediterranean region and the ‘unmaintained poplar plantations’ class complete the scheme (5%).

Table A.2. Proportion of different species for reforestation as a function of the selected GRECOS.

GRECO	Current target species	Replacement species	Justification for the choice

GRECO A	Other hardwoods and large oaks	Sitka spruce: 35 % Douglas fir: 20 % Grand fir: 20 % Hybrid larch: 15 % Coast redwood : 10 %	Increased productivity
GRECOs A et B	Corsican pine	Maritime pine: 65 % Loblolly pine: 20 % Douglas fir: 5 % Hybrid larch: 5 % Grand fir: 5 %	Depending to the GRECO and the soil type: replacement of diseased Corsican pines with more productive species
GRECOs A, B et C	Common ash	Poplar: 70 % Hybrid larch: 30 %	Replacement of diseased ash with more productive species
GRECOs C, D et E	Other hardwoods	Douglas fir: 80 % Hybrid larch: 20 %	Increased productivity
GRECO F	Other hardwoods and softwoods	Maritime pine: 70 % Loblolly pine: 10 % Eucalyptus: 10 % Douglas fir: 5 % Hybrid larch: 5 %	Increased productivity
GRECO G	Other hardwoods	Douglas fir: 70 % Hybrid larch: 15 % Grand fir: 15 %	Increased productivity
GRECOs F et G	Other hardwoods	Douglas fir: 40 % Maritime pine: 30 % Loblolly pine: 10 % Eucalyptus: 10 % Hybrid larch: 5 % Grand fir: 10 %	Increased productivity
GRECOs F, G zone ouest et I	Chestnut	Maritime pine: 70 % Loblolly pine: 10 % Eucalyptus: 10 % Douglas fir: 5 % Hybrid larch: 5 %	According to the GRECO and the soil type: replacement of the ageing chestnut trees with more productive species
		Atlas cedar:	

GRECO J	Other softwoods	100 %	Development of the better soils
Poplar class	Unmaintained poplar	Poplar: 100 %	Increased productivity

Similarly, for each species, one or more silvicultural pathways were proposed, and a breakdown of the pathways was applied (Table A.3). However, for the sake of simplicity, the breakdown of the different forestry pathways has been made identical regardless of the reforestation area in France (no regionalisation).

Table A.3. Breakdown of the different silvicultural pathways according to tree species.

Species / scenario	Conventional lumber (%)	Semi-dedicated (%)	Biomass (%)
Douglas fir	80	20	
Maritime pine	80	20	
Loblolly pine	80	20	
Hybrid larch	80	10	10
Eucalyptus			100
Poplar	90		10
Coast redwood		80	20
Grand fir	50	30	20
Sitka spruce	80	10	10
Cedar	100		

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