Matière à débattre & décider

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

éditions Quæ

The forestry & wood sector and climate change mitigation

From carbon sequestration in forests to the development of the bioeconomy

Alice Roux, Antoine Colin, Jean-François Dhôte
and Bertrand Schmitt, editors

Éditions Quæ

This book is a revised version of the study commissioned by the Ministry of Agriculture and conducted by INRAE and IGN in 2017. The contents of the study and of this publication are the sole responsibility of their authors.

The report and its annexes are available on www.inrae.fr/actualites/quel-role-forets-filiere-foret-bois-francaises-lattenuation-du-changement-climatique.

To cite this book: Roux A., Colin A., Dhôte J.-F., Schmitt B. (eds.), 2023. *The forestry & wood sector and climate change mitigation: from carbon sequestration in forests to the development of the bioeconomy*. Versailles, Éditions Quæ, 154 p.

This book is the English translation of:
Roux A., Colin A., Dhôte J.-F., Schmitt B. (coord.), 2020. *Filière forêt-bois et atténuation du changement climatique : entre séquestration du carbone en forêt et développement de la bioéconomie*. Versailles, éditions Quæ, 170 p.

The publication of these books has been financed by the Collective Scientific Assessment, Foresight and Advanced Studies (DEPE) of INRAE.

x.ISBN (eBook): 978-2-7592-3280-2
ISSN : 2115-1229

ISBN (print): 978-2-7592-3833-0
e.ISBN (pdf): 978-2-7592-3834-7

Éditions Quæ
RD 10
78026 Versailles Cedex

www.quae.com
www.quae-open.com

Contents

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, General Manager of IGN
Philippe Mauguin, Chief Executive Officer 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.

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.

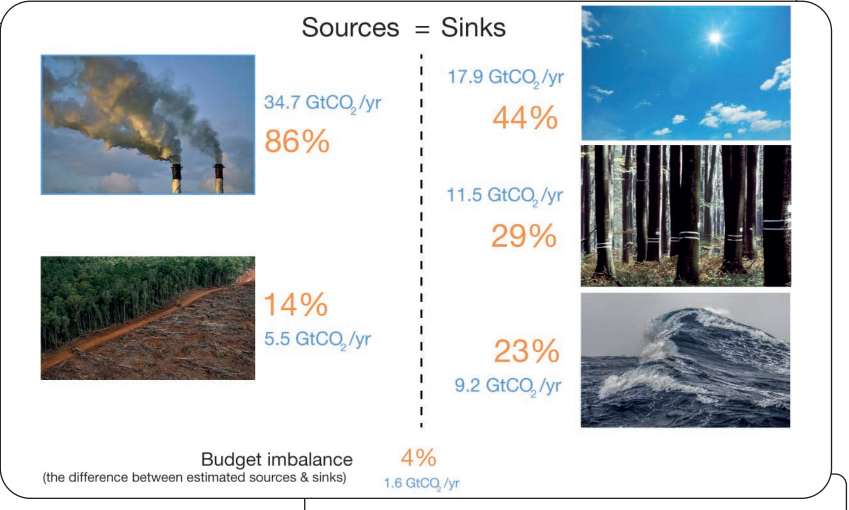
Forests make a major contribution to the global natural carbon cycle through highly significant exchanges with the atmosphere. The gross primary production of forests, i.e. the photosynthetic input of CO_2 into ecosystems, is estimated at 220 $GtCO_2$/year, i.e. nearly 50% of that of all terrestrial 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 I.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 I.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 I.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.

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 I.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).

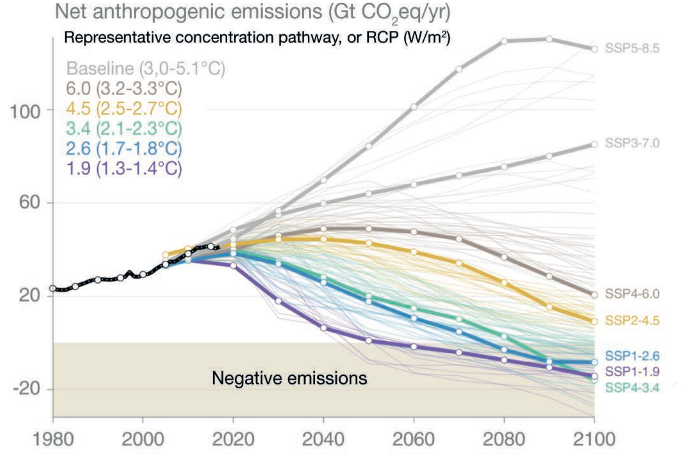


44% of total emissions remain in the atmosphere, while 29% of emissions are sequestered in terrestrial ecosystems (mainly forest ecosystems).

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 I.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.

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».

Figure I.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.

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

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).

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

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).

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.