# FOREST MANAGEMENT AND CLIMATE CHANGE

## A NEW APPROACH TO THE FRENCH MITIGATION STRATEGY

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# SUMMARY

Through this study, we have attempted to provide a deeper understanding of the evolution of the carbon sink represented by forests and the wood sector, in order to propose and analyse a strategy to optimise the role of forest management in mitigating climate change by 2050.

The climate role of forests and their management involves wide and complex areas of science. Although not exhaustive, the literature review demonstrates a rich and interesting breadth of work. The strategies currently proposed are sometimes contradictory and there are lively debates, in particular about harvesting rates and the emphasis placed on substituting non-renewable energy and materials by wood. This analysis shows that in order to store carbon, we will need to: (1) preserve and if possible increase above-ground and below-ground stocks through adapted forestry, (2) preserve and increase stocks in wood products, and (3) substitute wood for competing materials while limiting emissions generated by the wood sector.

We then study the maximum scope for increasing harvesting. Total net production of wood in French forests is estimated at 120 cubic megametres per year ($Mm^3/yr$) and the total harvesting rate at 50%. Taking into account physical limits, and land tenure and social barriers, the maximum area that can be harvested is estimated at 78% of French forest, i.e. 12.6 million hectares (Mha). By harvesting a total of 95 $Mm^3/yr$, we would harvest all net production from this area. This maximum potential for harvesting could only be attained following substantial efforts in terms of equipment and land consolidation. It assumes constant mortality and involves almost total extraction of branches and dead trees, which would have consequences for biodiversity and soil fertility. This hypothesis is further elaborated in the report.

To build a mitigation strategy and study its potential impacts, we first identify three typical forest management contexts in Metropolitan France (natural forests, forest stagnation, which we will term 'deadlock', and continuous cover forestry). A precise definition is given for continuous cover forestry, as well as for deadlock situations requiring reforestation through planting with a change in species. An optimal level of standing volume (at equilibrium) is estimated. Three harvesting scenarios are then defined, based on very different objectives (prioritising the sector, prioritising the ecosystem, compromise), assuming a constant surface area (16 Mha), and in two scenarios with annual mortality trends reflecting optimistic and pessimistic Intergovernmental Panel on Climate Change (IPCC) climate projections. In these scenarios, unmanaged areas account for 35% of forest in 2020 and 25% in 2050, of which 10% is legally protected natural forest, while the (replanted) deadlocked area represents 3% of French forest in 2020 and 4–7% in 2050 depending on the level of mortality, with the remainder being managed as continuous cover forestry. Harvesting rates for branches and dead wood vary from 10% (ecosystem prioritised) to 75% (sector prioritised).

The three scenarios studied lead to total harvests in 2050 ranging from 30 $Mm^3/yr$ to 95 $Mm^3/yr$, resulting from different progressions in harvesting rates for stemwood, branches and dead wood. Naturally, the "extensive" scenario optimises the development of stocks in the ecosystem, while the "intensive" scenario optimises the development of stocks in wood products. However, from the same starting point, the lower the harvesting, the higher the total carbon stock (ecosystem + products) in 2050. The annual carbon sink continually decreases in the scenario with increased harvesting, while it increases in the low harvesting scenario. These large variations in carbon stock will have consequences not only for biodiversity, but also for soil fertility and tree health, and thus for the ability of ecosystems to continue to produce wood without becoming dependent on expensive and energy-intensive inputs.

Beyond questions of ecological sustainability, increasing harvesting to 95 Mm³/yr by 2050 would require authoritative measures to utilise land and standing volumes. Conversely, reducing harvesting as in the extensive scenario could create a supply crisis in the wood sector, worsening sawmill closures and employment problems in rural areas and leading to increased imports. The scenario in which current harvesting rates are maintained therefore seems an attractive compromise, provided that harvesting is better distributed than at present.

We propose an enhanced mitigation strategy, based on: (1) making an explicit decision to leave 25% of the forest area to evolve naturally; (2) continuing to harvest at 60 Mm³/yr until 2050, increasing the managed area to provide better spatial distribution of this harvest, achieve a stock in equilibrium, and reduce harvesting rates of branches and dead wood; and (3) practising continuous cover forestry with high harvesting limits, combined in deadlock areas with even-aged high forest, through small patches planted with diversified species after minimal tillage.

In proposing increasing harvesting to 95 Mm³/yr by 2050, current national strategies (National Low Carbon Strategy, SNBC in French; National Wood and Forest Programme, PNFB in French; Afterre) do not address the impact of this approach on tree stress, biomass stocks in the ecosystem, soil fertility due to branch harvesting, biodiversity due to dead wood harvesting and the increasing scarcity of large- and very large-diameter trees, and conflicts of use. Such an approach can destabilise ecosystems, gradually increasing the need for short rotations and renewal by planting.

Any national strategy should be compared with strategies developed at the regional level with local actors, in order to test its practicality and provide a more concrete vision for the spatial distribution of harvesting. The literature, the scenarios developed and the calculation tool used in this study could enable dialogue based on regional simulations.

The subject matter is very complex and our study is not intended to answer the tough questions currently raised by climate change and the role to be played by forests and wood products. However, it provides a new perspective on the subject, shares knowledge and opens the discussion to a wide audience, so that the future of French forests is not decided only by those experts and politicians whose opinions are considered admissible.

# 1. CONTEXT AND OBJECTIVES

The average global temperature has increased by about 1°C since pre-industrial times. Several studies show that warming above 1.5°C brings significant risk of crossing a climate tipping point that could lead to runaway climate change (Moore, 2018). While it is very difficult to identify precisely when this tipping point may be crossed, it is certain that the coming decades will be crucial (IPCC, 2018).

The latest IPCC report (2018) on scenarios to limit global warming to 1.5°C above pre-industrial levels calls for rapid, far-reaching, and unprecedented changes in all aspects of society. The report estimates that the atmosphere cannot absorb more than 420 gigatonnes (Gt) of $CO_2$ if we are to attempt to stay below this temperature threshold. Each year, humanity emits about 42 Gt of $CO_2$ globally. This means that at the current rate we could pass this limit in nine years' time, and that there are 26 years left before we exceed the limit for 2°C of global warming. It should be possible to meet the 2°C target by reaching "net zero emissions" by 2050.

Forests are essential for absorbing carbon dioxide (IPCC, 2018) and keeping the global average temperature rise below 2°C, and as close as possible to 1.5°C (Paris Agreement, 2015). In France, forests represent a carbon sink currently estimated at -65 $MtCO_2$eq/yr (MTES, 2018a) with estimates of up to -87 $MtCO_2$eq/yr (Couturier, 2018; EFESE, 2019), or about 20% of $CO_2$ emissions in France. In the short term, improving protection for forests could be more effective than afforestation/reforestation programmes (IPCC, 2019), which can bring medium- to long-term benefits but also risks to food security and sustainable development (Searchinger et al., 2018; IPCC, 2019). Globally, terrestrial ecosystems currently absorb about one third of annual emissions (IPCC, 2018), with forests responsible for most of this absorption.

The debate on the contribution of the forestry sector has intensified in recent years, with the publication of several studies exploring different management scenarios (Roux et al., 2017; Valade et al., 2017). The public authorities' current approach is based on increasing forest harvesting (National Forest and Wood Plan, 2018) to maximise carbon storage in wood products, and on substitution with energies or products deemed to emit less $CO_2$ (MTES, 2018a).

This report explores another option to increase sequestration in forests and storage in long-life wood products. This strategy, known as "proforestation" (Moomaw, 2019), consists of increasing the area of natural forest and lengthening rotation times in managed forests, in order to approach optimum carbon storage in ecosystems. It has the dual benefit of maximising absorption of carbon dioxide over the coming decades and significantly increasing the naturalness of forests, and therefore their biodiversity. By exploring this pathway, this study provides a new perspective on the evolution of French forests and their contribution to climate change mitigation.

Before constructing a proposal, we analyse the recent scientific literature to avoid any inconsistency with current scientifically recognised realities. More specifically, we need to fully understand the forest carbon cycle and the natural and anthropogenic factors involved in this cycle, and then to familiarise ourselves with strategies currently being proposed.

# 2. LITERATURE REVIEW

## Introduction

In optimising the role of the forestry sector in climate change mitigation, four levers are traditionally identified: ecosystem storage, storage in products (sequestration), material substitution, and energy substitution (Pingoud et al., 2010; Werner et al., 2010; Madignier et al., 2014; MTES, 2018a). The French Environment and Energy Management Agency (ADEME, 2015) shows linkage between these levers in the diagram below.



*If wood harvesting is included in the variation in carbon storage in ecosystems, then $CO_2$ emissions related to the wood decomposition or combustion process in the sector should not be included so that they are not counted twice.
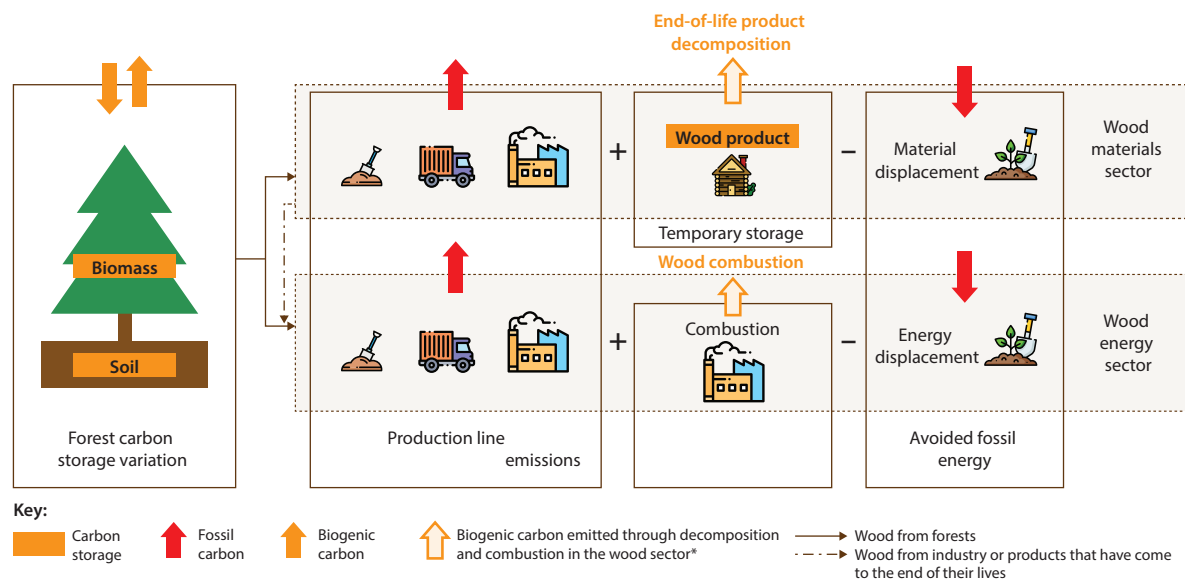
In this chapter, we detail the potential contribution of these different levers.

## 2.1. Carbon cycle and storage in forest ecosystems

French forests act as a "carbon sink", due to the absorption of $CO_2$ by photosynthesis exceeding emissions through respiration. The rate at which carbon "rotates" – between living organisms, the soil, wood products extracted from the forest, and the atmosphere – depends on the dynamics of sequestration and decomposition. Thus, the speed of sequestration and the level of carbon stocks are influenced by the climate, the soil, the plants being grown, and human intervention in all of these. The graph below shows the evolution of standing volumes over time in a forest without intervention, starting with a non-wooded area.

Thus, the older a forest, the greater its carbon storage. For temperate forests, Pregitzer and Euskirchen (2004) estimate the average carbon content of living biomass in the 120–200 year age group at 300 tonnes of carbon per hectare (tC/ha), for a forest density of 600 m³/ha.
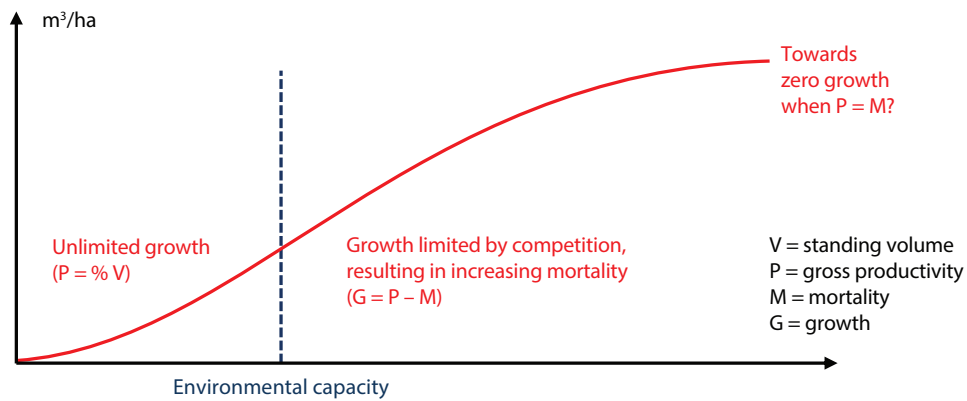
It has long been postulated that with age, a balance develops between respiration and photosynthesis (Odum, 1969). However, more recent studies show that the absorption capacity of old-growth and mature forests has been underestimated, such that this balance would occur asymptotically and only after centuries or even millennia. Although the carbon sequestration flow decreases as a tree ages, studies show that very large trees have high productivity rates (Stephenson et al., 2014) and that even very old and mature forests continue to provide significant carbon sequestration. Luyssaert et al., (2008) showed, through analysis of studies on 519 boreal and temperate forest plots, that: "in forests between 15 and 800 years old, the NEP [net ecosystem productivity] is usually positive; that is, the forests are $CO_2$ sinks". On the other hand, they observe that young forests are often sources of $CO_2$, because their creation (whether naturally or by humans) frequently follows disturbance to soil, resulting in decomposition of debris, litter and organic carbon. This decomposition exceeds, sometimes for several decades, the carbon reabsorbed through the growth of young trees.

Net carbon storage by old forests is still poorly understood, but could be due to the storage in soils of some of the carbon in dead wood. By studying forests over 400 years old in the Dinghushan Biosphere Reserve in China, Zhou et al. (2006) showed that organic carbon concentrations in the first 20 cm of soil had continuously increased between 1979 and 2003, from 1.4% to 2.35%. One could also assume a continuous rise in productivity through increasing overall efficiency in resource use (light, water, minerals) due to tree maturity, synergy between niches, and relationships between individuals and between species (symbiosis, cooperation, commensalism). The respective impact of these effects on mortality is a topical issue in research into forest ecology.

To understand carbon stocks and flows in the forest ecosystem, we therefore need to consider all carbon pools, including soil, which at the global level would represent a stock three times larger than that of the atmosphere (EFESE, 2019).

The diagram below summarises the carbon cycle in the forest-wood-atmosphere system.
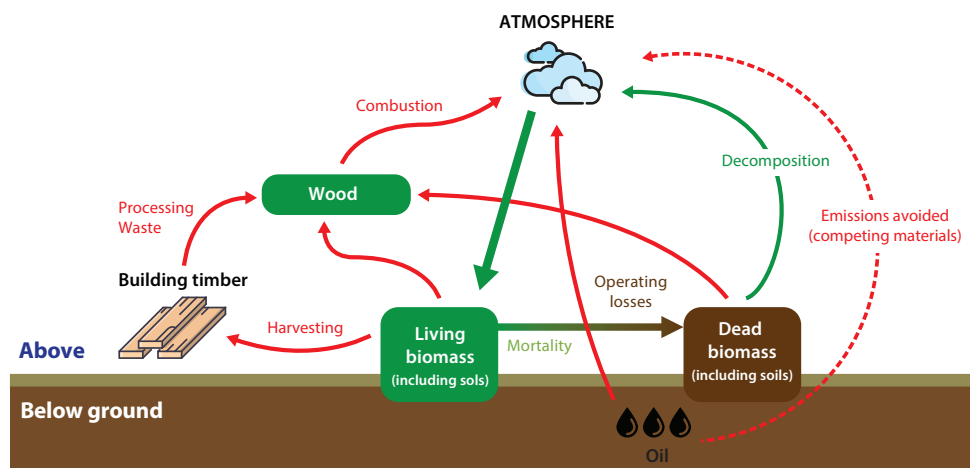
## 2.2. Carbon storage in wood products

When the wood from trees is harvested and then processed, some of the carbon absorbed during the tree's growth is stored in the products created. The storage life is defined by the lifetime of these products, which can range from a few days for a leaflet, to decades or even hundreds of years for a wooden building (EASAC, 2017). However, offcuts from the joinery and construction sectors are generally used for energy and paper, so they rapidly emit $CO_2$. Although a wood product does represent a carbon stock, the actual benefit of harvesting a tree depends on the lifetime of the product produced, which must be compared to that of the wood in the ecosystem if the tree had not been cut down.

Currently, the average half-lives recognised for products (*Centre national de la propriété forestière* – France's National Forest Ownership Centre – CNPF, 2017; European Commission) are 35 years for timber, 25 years for wood panels, 2 years for paper and 1 year for wood energy. For several decades, however, the construction and furniture industries have been using techniques that tend to reduce the lifetime of wood products (fine sawn wood, chipboard, panels).

## 2.3. Substitution effects

Several authors also recommend factoring in the substitution effects of using wood to replace competing energies or materials with higher carbon footprints (Pingoud et al., 2010; Werner et al.,,, 2010; Madignier et al., 2014; Vial, 2019). This is done by using displacement factors (DF) resulting, over a given time period, from the life cycles of wood and competing materials, and their impacts on other carbon pools (JRC, 2010).

The benefit of using wood has been cited for over a decade (Lippke, 2009) and is a major factor in French mitigation scenarios (Roux et al., 2017; Solagro, 2016; Couturier, 2018). However, there is a significant degree of uncertainty over the displacement factors, due to difficulties not only in predicting patterns in the use of wood and of alternatives (Roux et al., 2017; Vial, 2019), but also in modelling cycles and emissions generated through harvesting and processing raw materials.

The substitution effect is estimated through a factor showing the difference in carbon emissions per unit of material used (Sathre and O'Connor, 2010), as discussed below. Thus, a positive displacement factor represents a beneficial climate effect of wood use. This issue will be revisited in Chapter 4.

The **first type of substitution effect relates to the use of wood as a material.** Many studies show that the use of wood-based materials generally results in lower greenhouse gas emissions over the full life cycle, compared to the use of other materials, which require more grey energy in their processing. However, the factors attributed are determined on purely statistical bases (meta-analysis) and using questionable assumptions. Thus, the overall climate benefit of harvesting wood for use as a material is contested (Keith et al., 2015; Law et al., 2018), at least under current industry practices (Böttcher et al., 2018). This is because processing chains can differ significantly for the same wood product, depending on harvesting methods, transport and processing. In addition, ongoing changes in competing sectors can complicate comparisons. The displacement factor for wood used as a material thus ranges from 0.59 to 3.47 $tCO_2$eq per $m^3$ of wood used (Rüter et al., 2016; Roux et al., 2017).

The **second type of substitution effect relates to the use of wood energy to displace fossil fuels**. Energy substitution is probably the most debatable and complex concept to understand. 2018ven propose discounting it, as the effects are considered too contradictory in the literature (Böttcher et al., 2018). Indeed, whether energy is produced from wood or a fossil fuel, combustion unlocks carbon and emits $CO_2$. The $CO_2$ emitted through the combustion of biomass is chemically identical to that emitted from a fossil source (Leturcq, 2011; Haberl, 2012) and should therefore be included in emissions (Zanchi et al., 2012; Searchinger et al., 2018; Smyth et al., 2014; Sterman et al., 2018). The carbon stock replenishes faster with wood, but the effect of felling will only be zero

if the $CO_2$ emitted is immediately recaptured through an increase in photosynthesis caused by harvesting the wood. However, logging has a depressant effect on productivity – temporarily in the case of thinning and for several decades in the case of clear-cutting. Neutrality is therefore not immediate, and consideration must be paid to the loss of carbon sequestration that the trees could have continued to provide if they had not been cut down (Pelletier, 2018; Sterman et al., 2018). Although these variations in carbon flow should be incorporated into the displacement factors (Valade et al., 2017), they are generally not. Moreover, the factors often assume neutrality in external trade and do not include operating losses (Roux et al., 2017).

It is therefore impossible to consider the combustion of wood energy as climate neutral, as is often claimed in France (MTES, 2018a) and sometimes beyond (EU, 2003). This principle of neutrality also completely contradicts France's annual declarations of emissions to the European Union, where 20% is from wood combustion.

The benefit of displacement is obviously zero, or even negative if the reference energy source is carbon-free. Comparing it with other carbon energies, to deliver the same quantity of heat, wood emits more $CO_2$ than gas or oil (Allemand, 2003). Its carbon footprint increases if we consider the indirect emissions linked to the harvesting of wood energy (Leturcq, 2014). When wood is harvested in the forest, part of the harvest is discarded on site (branches, foliage, stump, etc.) and thus enters a decomposition cycle: part of the carbon will gradually be released into the atmosphere and another part stored in the soil. On the other hand, the extraction of non-renewable fuels emits more $CO_2$ than the extraction of wood. But taking into account "upstream" emissions means that wood does not have an advantage, according to Leturcq (2014) and Searchinger et al. (2018).

Thus, energy substitution with wood will only be climate beneficial if the emissions from the extraction-transport-processing chain, and the impact of harvesting on growth and soil carbon stocks, are low enough to make the life cycle assessment for wood advantageous compared to that for the energy source displaced. It will only be beneficial beyond a "return time" for carbon in the ecosystem ("carbon debt" or "payback time") determined by the photosynthetic capacity of the ecosystem, and therefore also by management practices (Agostini et al., 2013; ADEME, 2015; Martel, 2019b). Since these times are long, the use of wood for energy may not enable us to avoid the thresholds for runaway climate change (EASAC, 2017; Booth, 2018; Courvoisier et al., 2017; Schlesinger, 2018). Indeed, two recent studies (Roux et al., 2017; Valade et al., 2018) show that the carbon debt incurred by increasing harvesting takes at least 35 years to be paid back through displacement. These studies are consistent with the findings of the Joint Research Centre, which also concludes that payback times for this carbon debt range from several decades to over a century, depending on the type of wood used (Agostini et al., 2013). The table below summarises the factors involved.

| Biomass energy source | Short term (10 years) | | Medium term (50 years) | | Long term (centuries) | |
|---|---|---|---|---|---|---|
| | Coal | Natural gas | Coal | Natural gas | Coal | Natural gas |
| Harvesting of large stemwood in temperate forests for energy only | --- | --- | +/– | – | ++ | + |
| Harvesting of operating waste | +/– | +/– | + | + | ++ | ++ |
| Harvesting after extreme events | +/– | +/– | + | + | ++ | ++ |
| Forestry work for fire and disease prevention | +/– | +/– | + | + | ++ | ++ |

*Table 1: Assessment of the carbon return time if the additional wood harvest is intended for use. Source: European Commission Joint Research Centre (JRC), 2013.*

*Key: +/–: The net GHG emissions from the wood energy system and fossil fuels are comparable*
*–: the wood energy system contributes more to increasing atmospheric $CO_2$ concentration than the fossil fuel reference system.*
*+: the wood energy system contributes less to increasing atmospheric $CO_2$ concentration than the fossil fuel reference system.*

The European Academies' Science Advisory Council (EASAC, 2017) considers that: "The potentially very long payback periods for forest biomass raise important issues given the UNFCCC's [United Nations Framework Convention on Climate Change's] aspiration of limiting warming to 1.5°C above pre-industrial levels [...]. On

current trends, this may be exceeded in around a decade. Relying on forest biomass for [...] renewable energy, with its associated initial increase in atmospheric carbon dioxide levels, increases the risk of overshooting the 1.5°C target."

Thus, there is now no recognised climate benefit in releasing carbon from biomass to produce energy (Searchinger et al., 2018; Hennenberg et al., 2018; Collective, 2018). In addition, increased harvesting for energy could have negative effects on soil fertility (Achat et al., 2015a-2015b) and biodiversity (Bouget et al., 2012). There are thus significant tensions between biomass extraction and the environmental functions of forests (Bouget et al., 2012; EASAC, 2017). There is still intense debate over the benefits of energy substitution (Sterman et al., 2018; Prisley et al., 2018).

In general, there is significant uncertainty about displacement factors, and their usage also raises questions about forest management and product recovery. At the extremes, building onsite by felling and processing a tree without motorisation will generate a very favourable displacement factor, while building using a tree from a highly mechanised chain at the other end of the country could generate higher emissions than the competing material, and therefore a negative factor. It is therefore surprising that the techniques used for extraction, processing and transportation are not first order variables in the scenarios studied; they are some-what masked by the use of displacement factors, which are fixed and usually poorly justified. Finally, these factors generally assume carbon neutrality and felling neutrality, and do not include operating losses or combustion of timber-processing waste (Leturcq, 2014).

In summary, any substitution must be analysed from three angles: (1) the extent of the carbon debt generated by felling and the effect of felling on ecosystem storage; (2) the lifetime of the products created compared with that of wood left in the forest; (3) the carbon emissions generated by the supply chains for competing materials.

## 2.4. Impact of forest management decisions on the contribution of the forestry sector to combating climate change

Forest management can significantly affect the role of forests as carbon sinks. According to EFESE (2019), major destabilisation of French terrestrial ecosystems could generate up to 60 times the annual French $CO_2$ emissions of 2015. This potential destabilisation would only partially affect forests, but destructive forestry practices could also result in significant emissions. On the other hand, as explained above, the wood sector adds a carbon pool when harvested wood is put to long-term use.

The human factors influencing carbon stocks and flows in forests are detailed below. Although nearly half of France's forest has resulted from natural or human reforestation since the mid-19th century, the surface area of French forest has been almost stable since 2010 and it is becoming rare for agricultural land to be turned into forest. Therefore, we will exclude afforestation of agricultural land from the literature review and the 2020–2050 scenarios studied.

### 2.4.1. Share of forests and trees left to develop naturally

For over two decades, the harvesting of a large part of annual ecosystem biomass production for human activities has been considered a major threat to ecosystem sustainability (Haberl et al., 1997, 2007 and 2014). Taking 100% of biological production would impact forest ecosystems (EFESE, 2019), particularly in terms of biodiversity which would be severely impacted (Bouget et al., 2012), thus affecting soil fertility and the sustainability of primary production.

Despite the assumptions of some French authors (CGAAER, 2008; Peyron, 2015; Roux et al., 2017), there is currently no evidence that "natural" forests are more vulnerable to climate change than planted forests. The

resilience of natural forests to climate change has been demonstrated (Thompson et al., 2009) and there is abundant literature on the better resilience of mixed stands compared with single-species stands (Morin et al., 2014; del Rio et al., 2017; Jactel et al., 2017; Jactel et al., 2018; van der Plas et al., 2018; Sousa-Silva et al., 2018; Jourdan et al., 2019). The predominance of monocultures, intensive harvesting and changes in forestry pathways increase the impact of storms and biotic agents (Nageleisen et al., 2010; Lousteau et al., 2010).

Harvesting in itself has a direct influence on carbon stocks, by affecting stock levels and the buffer role of dead wood (Roux et al., 2017). Thus the proportion of forests that are not harvested can impact the role of carbon sinks, especially where forests are young, as is generally the case in France. Many authors have shown that expanding wilderness reserves increases carbon storage (Berry and Mackey, 2008; Chazdon, 2014; Keith et al., 2015; Wilson, 2016; Böttcher, 2018; Lewis and Wheeler, 2019). Some consider that spreading the idea that harvesting wood is always good for the climate ensures that forest management remains the dominant mitigation strategy, while in fact forest conservation has greater climatic and ecosystem impacts (Keith et al., 2015). In any case, the creation of wilderness reserves benefits carbon storage, as evidenced by the inclusion of this measure in the French National Strategy for Adaptation to Climate Change (MTES, 2018b). Finally, since ecosystems vary in their primary productivity and in their initial and potential stocks, depending on species, age and site (climate and soil), the nature of the unharvested areas can be equally decisive.

## 2.4.2. Cutting, standing volume and harvesting limits

In France, 50% of trees are less than 60 years old and 79% are less than 100 years old, with fairly large differences between species (IFN, 2018). This young population is easily explained by the natural pyramid of tree age. On the other hand, only 1% of trees are more than 200 years old, which seems very low compared to equivalent natural forests.

French forests are young overall (Roux et al., 2017) and increase by 27 Mm$^3$ per year, so they can still store carbon and mature (Hervé et al., 2016). A simulation at constant climate shows almost linear growth in carbon stocks until 2050 (Roux et al., 2017). French forests exhibit an average stemwood volume of 170 m$^3$/ha, a low level compared to most European forests (FAO, 2010; FCBA, 2018). For example, there are 321 m$^3$/ha in Germany, 296 m$^3$/ha in Austria, 218 m$^3$/ha in Croatia and 360 m$^3$/ha in Slovenia, so it is difficult to explain the French level simply because 17% of it is Mediterranean forest which is naturally less exploited (Veullien, 2016). It is a little surprising to see foresters frequently describe forests as "overexploited" when they are well below their potential volume if left natural (Martel, 2019a). For most species, current volumes are actually significantly lower than those recommended for continuous cover forestry according to the *Association Futaie Irrégulière* (Association for uneven-aged high forest) (Bruciamacchie M. and de Turckheim B., 2005; Pro Silva Europe, 2012). This important point will be further developed when we define the management scenarios studied

**Felling affects carbon stocks and flows in several ways:**

**1) Type of cutting (selective cutting or clear-cutting):**

While low-intensity thinning without soil compaction has little influence on the carbon cycle, clear-cutting affects biological balances and is detrimental to soil carbon stocks (Achat et al., 2015a-2015b; Rupil et al., 2019; Augusto et al., 2019). It also causes rapid mortality of root systems, foliage and undergrowth, accounting for up to 24 tCO$_2$eq/ha (Lousteau, 2010). Final cutting on established regeneration (renewal by shelterwood cutting) has less impact on soil and biodiversity, but could have a comparable effect on carbon stocks. Finally, since mineral content is higher when the tree is young (Ponette and Ranger, 2000), the practice of coppicing tends to deplete the soil due to the periodic harvesting of young wood.

Cutover (clear-cutting) of large areas has been common in France for several centuries, through the practice of simple coppicing and even-aged high forest. Comparison of National Forest Inventory (IFN in French) data shows that simple coppicing persists, and that even-aged high forest (i.e. clear-cutting or final cutting) has tended to expand in recent decades, mainly due to the increase in planted forests, which accounted for 14% of French forests in 2016 (IFN, 2018).

**2) Intensity and frequency in the case of selective cutting:**

Carbon storage is affected by the intensity and frequency of cutting, which according to some authors has already reduced the residence time of carbon in many boreal and temperate forests (Nabuurs et al., 2013; Law et al., 2018). Thus, the higher the rate of wood harvesting, the lower the storage rate. In the study by Valade et al. (2017) for example, the three harvest intensification scenarios for reducing fossil fuel consumption through use of biomass erode the carbon balance until some point between 2040 and 2080, depending on the case.

Regardless of the effects of soil compaction, the impact of cutting on soil carbon stocks is thought to be significant when more than 35% of cover is harvested (Augusto et al., 2019). Beyond 55%, there are losses of around 40% in plant litter and around 10% in the organic/mineral layer (Achat et al., 2015a-2015b). This impact is still poorly understood but does not currently seem to be taken into account in forestry scenarios to mitigate the effects of climate change.

The frequency and intensity of felling varies widely from one forest to another, but stakeholders in the field (e.g. National Forests Office (Office National des Forêts, ONF) unions) report an increase in harvesting, especially since 2000 due to mechanisation and harvesting being concentrated in low-cost forests. This point will be discussed in Chapter 3.

**3) Selected harvesting limit:**

The harvesting limit represents the age (rotation) or maximum diameter at which the forester harvests all trees. By comparing current practice with official sources, current harvesting limits range from 40 to 55 cm for softwood (40 to 100 years depending on species and site), 50 to 70 cm for beech (70 to 120 years), 60 to 80 cm for oak (120 to 180 years), 40 to 60 cm for precious hardwood (50 to 100 years) and 30 to 50 cm for poplar (20 to 40 years) and miscellaneous hardwood (40 to 80 years). It should be noted that harvesting limits are generally higher in continuous cover forestry (Pro Silva France, 2014). These limits have been subject to historical variation, with sometimes very low limits for coppicing (15 years in the Haut-Var). Most current policy reports recommend shortening cycles, in terms of diameter and age.

In 1981, the IFN estimated the stock of large-diameter trees (LD: D = 47.5 – 67.5 cm) and very large-diameter trees (VLD: D > 67.5 cm) at 339 Mm$^3$ (Pro Silva France, 2012b). In 2005–2009, stemwood volume was estimated at 421 Mm$^3$ for large-diameter trees and 125 Mm$^3$ for very large-diameter trees (IFN, 2010). In 2018, it was estimated at 522 Mm$^3$ (LD) and 169 Mm$^3$ (VLD), or 691 Mm$^3$ for LD+VLD (IFN, 2019a), which represents 25% of total volume (6% for VLD). Large-diameter trees are therefore increasing, but they mainly comprise oak, for which there is little difficulty in commercialising large-diameter timber.

Some authors believe that short cycles would be beneficial in addressing climate change (Peyron, 2015; Roux et al., 2017), but recent research shows the opposite (Martel et al., 2018; ADEME et al., 2018; ADEME, 2019). The higher the harvesting limit, the more carbon is stored in biomass (EASAC, 2017; Rupil et al., 2019) and older trees are both reservoirs and pumps, the individual efficiency of which increases with age (Stephenson et al., 2014). The carbon stock in soils would also be higher with long cycles (Rupil et al., 2019). Finally, long cycles physically reduce the frequency of major disturbance, and thus the potential release of soil carbon caused by these disturbances.

Pro Silva (2012) explains the roles of large-diameter trees in silviculture (education, stabilisation, regeneration, high value). The study shows the productivity efficiency of large-diameter trees, in relation to space occupied and cover. It also mentions the importance of large-diameter trees for the buffered microclimate that other trees and the soil require in order to optimise their functioning. It reminds us that very large-diameter trees are widely recognised for their role in preserving forest biodiversity, and that they have historical, landscape and social functions.

From an economic point of view, this study reminds us that operating costs are lower for large-diameter trees – and hence the related energy costs and carbon emissions are lower too. Sawing yield increases with wood diameter (Chalayer, 2015) although for poor and average quality wood, the profitability of sawing these woods with a bandmill is now greatly reduced due to competition from "canter" sawing. Thus the study shows that the harvesting limit must be defined much more according to the potential quality of the wood, as early harvesting can lead to significant losses. The difficulties in marketing large-diameter trees have much more to do with current wood usage than with the technical capacities of processing them (Chalayer, 2015). For the species and qualities demanded by the wood sector, such as oak, the risk thus comes down to the trees' biological and physical survival. Biological survival depends on multiple factors including climate change, but the IFN and Directorate of Forest Health (Direction de la Santé des Forêts, DSF) data seem to show fairly clearly that trees over 100 years old are statistically in greater decline than younger trees. As for stability, the idea that large trees are more sensitive to wind is disputed by the work of Dvorak et al. (2011), among others.

**4) Destiny of branches and stumps:**

Felling causes the tree to die, and with it the branches and generally also the stump, which gradually decompose and thus emit carbon; if the branches and stumps are not exported, felling thus causes "operating losses" (Lousteau et al., 2010). Leturcq (2018) estimates that overall these losses represent 50% of total volume harvested, i.e. a total of 0.5 GtC/yr for France, without considering the losses to soil and growth caused by cutting. However, it is likely that at least some of these "losses" will be incorporated into the soil and therefore stored in the ecosystem.

In addition, the harvesting of branches causes a loss of about 24% of the carbon stock in plant litter (Achat et al., 2015a-2015b) and the removal of stumps and branches depletes the soil in nutrient bases, reducing soil fertility and thus primary productivity, and therefore carbon storage (Lousteau et al., 2010; EFESE, 2019). According to Colin and Thivolle-Cazat (2016), to avoid soil fertility loss, the harvesting of smallwood (D < 7 cm) should be prohibited on at least 16% of forest soils in France and strongly discouraged on 21% of forest soils. However, productive forests in France are mainly located on acidic soils (IFN, 2015), which are more sensitive to soil base depletion.

## 2.4.3. Preferred or planted species

The IFN categorises 50% of French forests as "single-species stands" (IFN, 2010; IFN, 2014), which are largely the result of historic human management (planting, selective harvesting, coppice regime). However, at the plot (local) level, stands appear to be more mixed (IFN, 2015): 8% of surface area is estimated to feature a single species, 55% 2 to 5 species, 32% 6 to 9 species, and 5% 10 or more species. The threshold (basal area or volume) at which it is considered to be a mixed stand therefore needs to be specified. It is also noted that more than half of single-species stands are found in the southern half of France (IFN, 2010), due to the region's history of combining land clearing and reforestation under the national RTM and FFN programmes.

Diversified and undisturbed forests are recognised as higher carbon stocks than highly modified forests (CBD, 2014 and 2016; Mackey et al., 2015). In managed forests, stand composition is affected by cutting, planting and thinning. The preferred or planted tree species affect carbon stocks and flows, due to the following:

- sequestration through photosynthesis is higher when production is greater;
- the lifetime of the trees and their harvesting limit depends on the species, as detailed above;
- the duration of the products depends on their nature, therefore partly on the tree species used.

Some ecologists consider that plantations are not forests – or at least not yet – because of their history and characteristics (Dooley et al., 2018). Some detailed studies show net emissions due to species change by plantation (Naudts et al., 2016). Current literature demonstrates the advantage of mixed stands for resilience (see section 2.4.1), and most often positive effects on primary productivity (Jactel et al., 2018; Augusto et al., 2019). It also shows the advantage of mixed stands for wind stability (Colin et al., 2008; Knoke et al., 2008; Valinger

and Fridman, 2011; Griess et al., 2012; Diaz-Yanez et al., 2017). Finally, it shows the depressive effect of certain species on soil fertility, and therefore on their ability to fix carbon (EFESE, 2019). Carbon stocks in plant litter are higher for softwoods, but they are equal between softwoods and hardwoods over the entire soil profile (Augusto et al., 2015).

French strategies for the future now favour increasing the surface area of high-productivity species, a direction that some authors consider climate-positive (Roux et al., 2017) and others climate-negative (Grace et al., 2014). This sensitive issue is one of the elements of the strategies studied in this report.

## 2.4.4. Regeneration methods, tillage and soil improvers

According to the IFN (2018), trees resulting from stump regrowth represent in total 48% of countable trees (D > 7.5 cm) in French forests, but only 3% of trees with diameters greater than 32.5 cm.

A forest may be rejuvenated through large-scale cutover (even-aged high forest, simple coppicing), through small-scale or spot cutting (uneven-aged high forest, coppice selection method), or by large-scale cutting of a proportion of the stand (coppicing with standards, forest regenerated by shelterwood cutting). These types of cutting affect carbon stocks and flows as explained above. The climate benefit in increasing photosynthesis through planting, to the detriment of current stocks, is strongly contested in the international literature (EFESE, 2019; Naudts et al., 2016). Planting rather than natural regeneration is identified as unfavourable to the carbon balance (Augusto et al., 2019). On the other hand, converting coppice into forest is identified as favourable to carbon sequestration (Deheza and Bellassen, 2010). Broadly speaking, the current dominant trend is to retain simple coppice systems for poor sites and dry climates, and elsewhere to renew forests through canopy removal, whether for planting or natural regeneration. However, maintaining the simple coppice system and clear-cutting carries risks for the future. Clear-cutting complicates natural renewal, even in coppice, as the stumps eventually become depleted, causing problems in tree growth or health. Large-scale cutting also causes fragility through exposure, both biological (transpiration, sun damage) and physical (exposure to the effects of wind).

The soil preparation generally undertaken before planting can release carbon through soil exposure and compaction (Augusto et al., 2019), in addition to fossil carbon emissions through the use of machinery. Tillage before planting induces 35% carbon loss from plant litter, which manual planting does not produce (James and Harrisson, 2016). Soil compaction and tillage can discourage mycorrhizae and constrain root function and thus impact the health of trees (Nageleisen et al., 2010) and their productivity and longevity.

To make planting more successful, forest management sometimes includes the addition of ash, crushed rock or fertiliser to the soil. These inputs may temporarily increase photosynthesis, but they disrupt soil communities (Ecofor, 2016) and may thus discourage mycorrhizae activity. EFESE (2019) reports the risks of high soil mineral removal resulting from high-productivity species and short rotations. On acidic geological bases (the majority of French forests), these practices would lead forest managers to regularly apply soil improvers to avoid productivity loss and dieback which would weaken biological activity and increase the need for soil improvers.

## 2.4.5. Health aspects

In the context of climate change, the risks of dieback and its impact on carbon stocks cannot be neglected (Robinet and Roques, 2010; Choat et al., 2012; Reichstein et al., 2013). Tree mortality leads to $CO_2$ emissions. It results from competition between trees, climatic stresses and their interactions with pathogens (Jactel et al., 2012), and also from human behaviour (Nageleisen et al., 2010). Thus, sudden exposure by cutting can lead to mortality, as can soil compaction or skidding damage to trees. As emissions generated through mortality can negate the benefit of sequestration (Galik and Jackson, 2009; Seidl et al., 2014), management practices and changes in health can be critical to the role that forests will play in mitigating climate change (Roux et al., 2017). We will examine this subject in more detail in Chapter 3, through the notion of a health deadlock and the use of mortality rates.

### 2.4.6. Wildfires and storms

Wildfires cause rapid and extensive release of carbon from ecosystems. At the global level, they appear to have become more likely and widespread since 1975 (Ruffault et al., 2016; IPCC, 2018; meteofrance.fr). Although forest managers cannot control outbreaks, risk monitoring through the Défense des *Forêts Contre l'Incendie* (Protecting Forests Against Fire, DFCI) and silvicultural and pastoral practices can to some extent limit the spread of fires and their impact. For example, creating and maintaining wide access routes and firebreaks, crushing slash and undergrowth at the edge of frequented areas, and maintaining vertical gaps in vegetation can reduce the spread of fires. With increasing temperature and winds, sudden exposure of undergrowth can encourage the outbreak and spread of fires, especially where there is logging slash (branches, windrows).

Storms can also cause a release of forest carbon through windthrow leading to a subsequent harvesting or to progressive decomposition of the wood if it is not collected. Moreover, storms can decrease photosynthesis by affecting the standing volume and the stability of forest stands. Over the last 30 years, the most damaging storms for French forests took place in 1999 (Lothar & Martin) and 2009 (Klaus).

### 2.4.7. Biophysical factors

These are phenomena produced by the interaction between climatic factors and living organisms, more specifically variations in evapotranspiration due to land cover (albedo effect). Hardwood and mixed forests provide greater climate benefit (EASAC, 2017). However, in France, albedo differences between hardwood and softwood are limited due to the relatively small areas and periods of snow (Martel, 2019a).

### 2.4.8. Products created and emissions generated through wood extraction

The diagram on the following page, prepared by INRA (2018), summarises flows in the wood sector. Products created by the sector – usually determined from the point of felling – affect carbon storage through the lifetime of the products made, the duration of carbon sequestration, and the substitution effects. The lifetime can range from 1 year to over 50 years (CNPF, 2017), sometimes exceeding the lifetime of wood left in the forest. The principle of "cascading use" requires that wood with the potential to be sawn timber be used as little as possible for pulp, to avoid the associated losses of carbon and value (Pro Silva France, 2012a; WWF, 2016). This aspect is addressed in Chapter 4.

"Upstream emissions" represent the $CO_2$ emissions from machines used in forestry work, extraction (felling and skidding), transport and processing of harvested wood. Although transport can have a significant impact on the carbon footprint (Cosola et al., 2017), according to some authors (Leturcq, verbally), these emissions would not exceed 10% of the total carbon emissions of the cycle from felling to use of the finished product. However, this estimate depends on many factors and there seems to be little literature on the subject. As explained above, this lack of precision increases the uncertainty when using displacement factors in life cycle assessments.

In the current context, the net trend is towards an increase in fossil energy consumption per m³ exploited, due to mechanisation and the increase in transport distances caused by the drop in the number of processing units and the globalisation of trade (Chalayer, 2019). However, the impact of the choice of working methods does not seem to be integrated into the studies on mitigation strategies.

## 2.5. Current mitigation strategies

On a global and European scale, there has been an increase in scenarios in recent years. Below are some recent studies relevant to this report. These strategies show sometimes diametrically opposed views on the role of forests and the wood sector in climate change mitigation, particularly with regard to harvesting intensities, regeneration strategies and the benefits of substitution.

**Forestry sector flow in France**

Model: France forestry 1.0/July 2018.
Average period: 2009–2015.
Units: Thousands of m3 eq. wood fibre.
Key:

- Standing timber
- Timber
- Industrial wood
- Wood energy
- Waste
- Pulp/Paper

Products

Sectors

**AF Filières project: www.flux-biomasse.fr**. Partners and sponsors:

11212    Paper and cardboard (I)
61    Parquet (I)
2258    Panels (I)
548    Plywood (I)
810    Pallets and packaging (I)
160    Pellets (I)

27428

4974

3725

Household heating

1271

Other industrial and collective heating

3158

3965

5599

On-site recovery

2739

Wood waste

1857

Panel plants

Panels

7162

5186

Veneer

104

Plywood

340

Sleepers

Stave wood

2106

Parquet manufacturing

52

Parquet

687

Sawn timber F

24

146

Waste

1302

Pellet production

1303

Pellets

119

99

End use – second and third processing

40
519

28

584

821

560

Sawn timber R

3987

579

Wooden packaging manufacturing

5458

6621

Pallets and packaging

7033

End consumption

Pulp

Paper and cardboard manufacturing

6794

Paper and cardboard

19064

10517

17310

14691

Veneer (E)    126
Paper for recycling (E)    5909
Pulp (E)   1041
Sleepers (E)    131
Sawn timber R (E)    849
Sawn timber F (E)    482
Waste (E)    672

Paper for recycling

Panels (E)    4233
Paper and cardboard (E)    9457
Pellets (E)    193
Pallets and packaging (E)    397
Parquet (E)    14
Plywood (E)    201

19

| Study | Scope | Period | Scenarios |
|---|---|---|---|
| Colin et al., 2014 | Metropolitan France | 2020–2030 | 2 scenarios: Continuation of current practices – Proactive (increase in harvesting, reduction in harvesting limits, plantations). |
| Roux et al., 2017 | Metropolitan France | 2018–2050 | 3 scenarios: Extensification (26% less harvesting by 2050) – Regional action (simplification and specialisation in silviculture + continuation of current harvesting) – Intensification (40% more harvesting by 2050 and major reforestation plan). |
| Valade et al., 2017 | Metropolitan France | 2010–2050 | 5 scenarios: Continuation of current practices – Intensification of harvesting in all managed forests (m) – Thinning in all "over-dense" forests (o) – Extraction in all "over-mature" forests (d) – Combined scenarios (m + o + d). |
| Dooley et al., 2018 | World | 2019–2050 | 1 scenario: Stop deforestation / increase forest area by 350 Mha through expansion and planting / increase the surface area of natural forests by 25% to achieve a total of 50% / use managed forests in a "responsible" way (extend cycles, reduce ground disturbance, etc.). Substitution effects unrecorded. |
| Böttcher et al., 2018 | Germany | 2019–2100 | 3 scenarios: Continuation of current practices – Restructuring through planting (increase in harvesting, promotion of softwood) – Forest Vision (increase in areas left natural, increase in harvesting limits, reduction in harvesting, preference for hardwoods). Substitution effects unrecorded. |

"Extensive" scenarios increase carbon stocks in the ecosystem but reduce harvesting, whereas "intensive" scenarios are measured through the products and their substitution effects. In studies developing the intensive option, extensive scenarios are sometimes defined inconsistently, with managers considered "passive and poor at anticipating change", compared to intensive managers who are described as "active and enlightened" (Roux et al., 2017). In this approach, intermediate and more subtle scenarios are not tested, although this would be possible and of interest (Martel, 2019).

The intensive scenarios carry significant risks, in terms of reduction in carbon stocks between 2020 and 2050, the weight given to energy and material substitution effects, and the impacts of the heavy harvesting and planned reforestation on soil fertility and biodiversity (high-productivity species, short cycles, slash harvesting, etc.). "Natural" forests are also presented as more vulnerable than plantations (Peyron, 2015), which goes against current literature. In an in-depth study, Lousteau et al. (2010) showed that intensive forestry scenarios and certain productive species such as poplar are more sensitive to climate change. In addition, links forged between species through coevolution could increase the resilience of both individual trees and ancient ecosystems. Finally, we could also assess the emissions generated by planting programmes and the carbon footprint of sectors that are based on small-diameter wood.

In the following chapter, we develop a national strategy that seeks a compromise between these different approaches, to maximise the role of forestry and the wood sector in multifunctional forest management.

# 3. STRATEGIC PROPOSAL

## 3.1. Introduction

In a business-as-usual scenario, achieving carbon neutrality would imply a 90% reduction in $CO_2$ emissions in 2050, compared with 1990 levels (EFESE, 2019). At the Grenelle Environment Forum (2007), France committed to reduce its emissions to one quarter of their 1990 levels by 2050. However, according to Luyssaert et al. (2018), although the climate effects and mitigation potential represented by forests are significant, they are still modest in relation to the challenge and the urgency. **Thus, reducing emissions must remain the absolute priority**. Mitigation efforts focusing on forests must be limited to emissions that are unavoidable even after implementing policy that combines sparing use, energy efficiency and the use of low-carbon renewable energies (solar, wind, hydro).

The proposal made here consists of optimising the climate role of French forests, while safeguarding the rest of their ecosystem services:

- preserving biodiversity and in particular species and habitats typical of forests;
- preserving soil stability and fertility;
- protecting surface water quality and regulating its flow;
- providing material resources and preserving and developing quality (attractive) local jobs;
- enabling the development of educational and tourist services in forests.

In developing this proposal, we consulted several studies (Angerand et al., 2014; Rossi et al., 2015; Lebreton, 2015; Valade et al., 2017; EASAC, 2017; Böttcher et al., 2018; Dooley et al., 2018; IUCN, 2018) and based our positions on the literature summarised in the previous chapter. While there are many publications on climate mitigation, it is still quite rare to find ones addressing concrete choices in terms of forestry and industry in the context of French forests.

Since the objective is to stabilise the climate at +1.5°C (IPCC, 2018), the study assumes the Representative Concentration Pathway (RCP) 2.6 to 2050, which INRA used in a major study on the subject (Roux et al., 2017). This is a fairly safe choice as the scenarios mainly differ after 2050, which is the threshold for possible runaway climate change. Although the increase in atmospheric $CO_2$ produces an increase in photosynthesis (Seguin, 2010), in the RCP 8.5 scenario (compounded climate change) beyond 2050 this increase would be cancelled out by the suppressant effect of temperature, which could be further reinforced by a decrease in fertility and problems in mineral assimilation by trees (Martel et al., 2019). Predicting the role of forests beyond 2050 is therefore particularly challenging and, unlike Roux et al. (2017), we will not risk relying on the benefits of management choices beyond 2050. However, we will test the scenarios in a context of high mortality, which is unfortunately possible.

The literature reviewed in Chapter 2 shows that to store carbon, we will need to: (1) preserve and if possible increase above-ground and below-ground stocks; (2) preserve and increase stocks in wood products; and (3) substitute wood for competing materials, if the emissions generated by the wood sector are lower than those generated by the competing sectors.

The proposals are designed for Metropolitan France, including Corsica. The case of poplars is treated separately, under "go with the flow" management (continuation of current practices).

To develop the strategic proposal, we start by studying the volumes currently harvested, the areas that can actually be managed given the obstacles, and the corresponding extractable volumes. This study, inspired by the ADEME protocol (Colin and Thivolle-Cazat, 2016), enables us to estimate the potentially harvestable volume, in order to frame the scenarios.

## 3.2. An essential prerequisite: Analysing the limits to increased harvesting

### 3.2.1. Area managed, productivity and current harvesting

For at least a decade, the surface area of French forests and natural environments has appeared to stabilise or even slightly decrease, mainly as a result of urbanisation. For example, the General Commissariat for Sustainable Development (CGDD, 2015) shows that between 1990 and 2012 this surface area decreased from 18.8 Mha to 18.6 Mha, while artificial environments gained 0.5 Mha (+20%) and agricultural environments remained more or less stable.

The area of forests covered by a sustainable management document (Simple Management Plan – PSG in French; Standard Management Rules – RTG in French; Code of Good Forestry Practice – CBPS in French) is estimated at 7.6 Mha (IFN, 2015), or 48% of French forests. In practice, part of these areas is not or is hardly exploited, while part of the 52% without documents is exploited. It is difficult to estimate the area of forests actually affected by wood harvesting in 2019; Valade et al. (2017) estimate the proportion of "actively managed" forests at 63%, so it is likely that the current base for logging is around 65%, a figure that we will apply for the remainder of the study.

Regarding the volumes produced and harvested, to avoid any confusion, we provide a reminder below of the conventional breakdown of a tree's biomass (Colin and Thivolle-Cazat, 2016):

Stemwood = main stem of the tree up to 7 cm diameter;
Total timber = stemwood + branches up to 7 cm diameter;
Above-ground biomass = total wood in stem and branches;
Root biomass = total root wood;
Smallwood = above-ground biomass – total timber.

Excluding cultivated poplars, the annual gross productivity of stemwood overbark from forests in Metropolitan France is currently estimated at 91 Mm³/yr, and mortality at 9 Mm³/yr (IFN, 2018), i.e. 82 Mm³/yr after mortality has been deducted (net productivity). The IFN figures are from the period 2008–2016, so in 2019 actual mortality is likely to be 10 Mm³/yr. The figures do not include harvesting following severe storms, in particular Cyclone Klaus in 2009, which generated 41 Mm³ but reduced subsequent harvests. As gross productivity may be lower (86 Mm³/yr according to FCBA, 2018), we will use the values of 90 Mm³/yr for gross and 80 Mm³/yr for net productivity. Using the expansion factors in Lousteau et al. (2010), total productivity of above-ground wood amounts to 135 Mm³/yr (gross) or 120 Mm³/yr (net). Average total net productivity (stem + branches) in France would therefore be 7.5 m³/ha/yr.

The National Low Carbon Strategy (Stratégie Nationale Bas-Carbone, SNBC in French) (MTES, 2018a) provided figures for 2018, showing total gross productivity of 125 Mm³/yr and total felling of 70 Mm³, with operating losses of 10 Mm³/yr.

According to the IFN (2019), a total of 45 Mm³ of stemwood was harvested in 2018, i.e. 50% of gross productivity or 56% of net productivity. Coniferous trees (softwood) are harvested at 69% and deciduous trees (hardwood) at 47%, with some species harvested at less than 40% (pubescent and holm oaks, miscellaneous hardwood); almost two thirds of harvests are taken from forests that are easy to harvest. Seventy-one per cent of the volume is harvested in private forests (which represent 75% of the surface area).

IFN data is based on field observations but only gives figures for stem wood harvest and not total harvests. The numbers from annual industry surveys and household energy consumption surveys through the French

research institute CEREN for the period 2011-2015 give a total harvest of 53 million m³/year without harvesting losses (estimated at 7 million m³/an). The databases are old (2006 for CEREN) and 'household' harvests are clearly underestimated (According to CNPF, 2017 figures would be closer to 25 million m3/year instead of 15). With 21.5 million m³/an of household harvests, FCBA (2018) estimates 2016 harvest to total at 59.4 million m³/year.

Ultimately, the figures we will use for current productivity and harvesting are as follows:

| | Productivity (Mm³/yr) | | Harvesting * (Mm³/yr) | Harvesting rate as % of P-net * |
|---|---|---|---|---|
| | Gross | Net | | |
| Stemwood | 90 | 80 | 45 | 56% |
| Total above-ground timber | 135 | 120 | 60 | 50% (+ losses 8%) |

*Operating losses deducted.*

It is more reliable to use net productivity as a reference, as harvesting due to mortality is not estimated separately. Given the exclusion of major windfall (for example caused by Cyclone Klaus), the harvesting figures above may be underestimated. In all cases, the figures carry uncertainty of around 10% according to IFN, the French Ministry of Agriculture and Food (AGRESTE in French) and ADEME.

According to FCBA (2018) and the General Commissariat for Sustainable Development (CGDD) (2019), energy production from wood is around 10 Mtoe (tonne oil equivalent) per year, which corresponds to 49 Mm³/year, or 81% of the total harvest. This figure seems high and could mean that the actual total harvest is higher than current estimates or that wood energy yields have been underestimated. Demand for wood energy is increasing, but the large margin for improvement in combustion equipment should reduce consumption per heating unit in the future.

If the logging base represents 65% of French forests, assuming 10% higher productivity in these forests than in the 35% that are unmanaged (more frequently young and/or on poor sites), the managed forests would produce 57 Mm³/yr of stemwood and they would experience a harvesting rate of 80%. The 75% estimate used by the ONF unions (CGT-forêt and SNUPFEN Solidaires) therefore does not seem too high. Naturally, it is not at 100% given the young plots, which need time to grow before they can be cut. Some foresters in these unions believe that the rates are even higher in state-owned forests.

Current potential for increasing harvesting must be analysed with regard to biological productivity and mortality, but also with regard to current harvesting and to all technical and land tenure barriers to extracting the untapped balance.

### 3.2.2. Obstacles to wood extraction

**1) Exploitability**

Technical difficulties in extraction include several factors (IFN, 2012a):



| Track | Terrain | Viable (even and load-bearing) | | | Unviable (uneven and wet) | | |
|---|---|---|---|---|---|---|---|
| | Slope / Skidding distance | 0-15% | 15-30% | > 30% | 0-15% | 15-30% | > 30% |
| Existing | < 200 m | | | | | | |
| | 200 - 1000 m | | | | | | |
| | 1000 - 2000 m | | | | | | |
| | > 2000 m | | | | | | |
| To be created | Any | | | | | | |
| Impossible | Any | | | | | | |

*Exploitability* ▢ *Easy* ▨ *Average* ▨ *Difficult* ▨ *Very difficult*
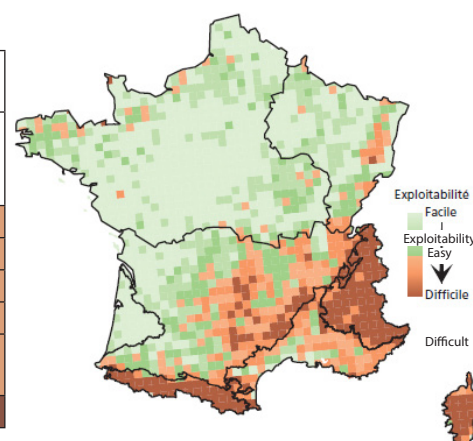
Currently:

- **one third of French forests are considered difficult or impossible to exploit**, according to the table above (13–68% depending on the species). These areas are mainly located in mountain regions, with high afforestation rates, mostly softwood (IFN, 2012a) and currently with the lowest harvesting rates. Thus, for species such as silver fir, Scots pine, Norway spruce and beech, half their current volume is classified as difficult to exploit (IGN, 2018). In reality, 64% of productivity is harvested in areas that are easy to exploit and 36% in areas that are difficult to exploit (IGN, 2018);

- 7% is located on inclines greater than 60% (difficult or even impossible to exploit), i.e. 21% of forests that are difficult to exploit;

- 10% is located on rough to very rough terrain, i.e. 30% of forests that are difficult to exploit;

- skidding distances are estimated to exceed 1 km for 6.4% of the areas (IFN, 2019a), areas from which only 31% of productivity is currently harvested (IFN, 2014; IFN, 2019a);

- 1% of forest soils would never be load-bearing and 75% are temporarily non-load-bearing (IFN, 2012a), thus imposing a limitation on working periods and tonnage;

In addition, there are **other obstacles**, making some areas unusable due to:

- development made impossible or extremely expensive due to black spots (villages with narrow access, mountain streams, rocky barriers, boulders, scree and unstable terrain);

- transport costs that are too high in relation to the value of the wood delivered, due to the increasing scarcity of sawmills;

- trees exceeding the diameter technically possible to saw (referred to as "over-mature" by some authors, including Valade et al., 2017).

One could also consider the carbon footprint, from logging to delivery of the wood, which in some cases would be too high to justify harvesting.

Considering all these obstacles, for this study we will consider that at least 25% of the areas that the IFN classifies as difficult to exploit are definitively non-exploitable and that **33% could not be exploited by 2050**, which gives 0.33 x 33% = **11% of French forests**. In our scenarios, this 11% is broken down by species, according to IFN estimates.

**2) Land tenure barriers**

Of the 89% of areas considered physically exploitable by 2050, the majority is in communal forests and in small unmanaged private forests. Yet for harvesting to be feasible, it must be legal and done with the owner's permission. Thus, in addition to this technical analysis, there are currently many **land tenure and social barriers.** The importance of these barriers between now and 2050 is quite difficult to estimate but they cannot be ignored:

- The protection status of the forest due to major challenges relating to the ground (landslides, proximity to built-up areas) or to water (peat bog, catchment areas, flood flows), as these barriers can affect exploitation of the forests concerned, as well as service roads to adjoining forests. In 2015, there were 0.35 Mha of protected forests in France (IGN, 2015), equating to 2.2%, but these are often exploited. On the other hand, some high-stakes areas are currently not legally protected. Consequently, we estimate these areas at **2%**.

- Protection status due to high biodiversity stakes (heritage value, connectivity). Currently, forest wilderness reserves cover 0.02 Mha in France (0.1%); Core National Park Areas 0.15 Mha (0.9%); reserves (national, regional and Corsican nature reserves, non-intervention and managed biological reserves, non-intervention National Park reserves), senescence islands in state forests, and biotope protection orders 0.23 Mha in total (1.4%); making a total of 2.4% but with possible overlap and 60% under controlled exploitation (Cateau et al., 2017). On the other hand, some high-stakes areas are not currently under legal protection. We will thus apply **2%** of surface area.

- The black spots described above may also affect physically exploitable forests located downstream and with no alternative access: we estimate this surface area at **1%**.

- The tourism role of forests, which can have a significant influence on silviculture (see ONF Île-de-France) but also limit potential harvesting. We will apply **1%**.

- Fragmentation (size and dispersion of units), which even with very long and expensive consolidation protocols (such as AFAFE) cannot solve all technical and human problems. We will apply **5%** of surface area.

- The freedom of the owner, who can choose not to exploit his or her forest or to operate only occasional and limited harvesting for domestic use. At least a quarter of owners of between 4 ha and 10 ha may be inclined to refuse logging (Maresca and Picard, 2010; Didolot and Thomas, 2015). For this criterion we will apply **4%**.

The total would be 15%, but some limitations may overlap. Thus, for physically exploitable forests, we will be cautious, applying an **overall rate of 12% for land tenure barriers, i.e. 11% of French forests**.

### 3.2.3. Manageable areas and limits to increasing harvesting

Considering all the obstacles to extraction described above, we obtain a **total of 22% of the area being non-exploitable area (11% + 11%) and 78% being potentially exploitable, i.e. 12.6 Mha.** Based on the productivity table above, this area would produce a total of 95 Mm³/yr net, or 63 Mm³/yr of stemwood.

If we harvest 100% of net biological productivity from the 12.6 Mha that can be exploited between now and 2050, **we could harvest an additional 18 Mm³/yr of stemwood** (operating losses deducted), or 35 Mm³/yr of total timber, giving a **total harvest of 95 Mm³/yr**. This maximum is aligned with current conventional scenarios for increasing harvesting since Sarkozy's speech in Urmatt in 2009 (Solagro; ADEME; Ministry of Agriculture, Food and Forestry – MAAF; Ministry for the Ecological and Inclusive Transition of France – MTES). However, it assumes that many current land tenure barriers will be lifted (fragmentation, access), some of which may be underestimated here, and most importantly:

- It does not take into account the likely increase in mortality rates.

- It does not take into account areas that are currently under-capitalised because they are young or impacted by storms (e.g. Landes).

- It implies either the total extraction of branches (100% of net productivity), which is physically impossible and would impact the soil (not to mention the energy balance), or high harvesting of natural mortality, which can be technically difficult and will impact biodiversity.

These limits were already indicated by the IFN in 2005 (IFN, 2005). The prospect of taking 95 Mm³/yr is therefore an absolute maximum, which cannot be reached quickly and will have significant ecological consequences. We will study this option in detail.

The 2020–2050 mitigation strategy developed in this report includes two additional limitations to harvesting:

- the necessary increase in standing capital in young stands, which entails harvesting less than net productivity;

- the need to increase the surface area left natural and the volumes of dead wood, to ensure the proper functioning of ecosystems and maintain biodiversity.

## 3.3. Pillar 1: Preserving and increasing carbon stocks in the ecosystem

The National Low Carbon Strategy (MAAF, 2018) emphasises the importance of conserving current carbon stocks. Increasing carbon stocks in existing forests is a cost-effective measure to increase the carbon sink (EASAC, 2017). The first strategy is to leave a large overall surface area natural, as explained in Part II. The second

is to preserve and increase stocks in managed forests, i.e.: (1) maintain forest cover to preserve fertility and biological balances and ensure the continuity of primary productivity; (2) gradually reach the maximum stock of standing timber compatible with continuous harvesting and regeneration.

### 3.3.1. Expanding and safeguarding natural forests

The positive role played by natural forests and high carbon stocks per hectare is recognised, as explained in Part II. In our strategy, the area under management in 2020–2050 excludes the 22% of area that is non-exploitable, as described above. Of this 22%, it is estimated that 7% could be classified as wilderness reserve to safeguard its role in terms of carbon and biodiversity.

For reasons of both habitat diversity and connectivity (gene flow), we need to preserve not only forests that are within non-exploitable areas. We therefore propose voluntary establishment of 4% of all "exploitable" French forests as natural areas, i.e. 3% of total French forests. This would lead to in total **10% being legally and sustainably classified as natural areas (1.6 Mha)** with the status of, for example, a wilderness reserve (RBI in French). This 3% is distributed among species according to the ecological value of the ecosystems (species, presence of large- and very large-diameter trees, health risks to delay mortality, economic value of wood to reduce losses in economic value added). It is also important to distribute the areas among all territories, with large and small wilderness reserves and corridors linking them, including senescence islands in forests managed by the ONF (Single Large or Several Small ["SLOSS"] type optimisation: Diamond, 1975; Wilcox and Murphy, 1985).

Thus, in the proposed management scenario, **3% of French forest** is voluntarily left natural, in addition to the 22% that is non-exploitable, i.e. a total of **25% of French forest (4.0 Mha)** not harvested between 2020 and 2050. This aligns with the recommendations of Dooley et al. (2018).

### 3.3.2. Renewing stands in deadlocked areas

The **concept of "deadlock"** has gradually entered the current vocabulary of foresters without being well defined. According to CNPF (2018), it describes a plot of land "doomed to halted growth in the absence of renewal", due to a stand that is "off-site, in poor health, unstable or experiencing dieback". The term thus includes considerations about the biological survival of trees and their productivity, which are usually not clarified:

- the minimum growth expected by the forester is not defined;
- the "off-site" qualification is meaningful only if a purpose and time period are defined;
- the qualifier "in the absence of renewal" relates to the species, densities and the rate of installation and production expected by the forester;
- the assessment of stability (which mainly concerns stands in very windy positions and/or "late thinning") is often affected by the imposed cutting pattern (heavy thinning), which increases this instability to the point of condemning the stand following the operation;
- "dieback" is linked to resilience capacities and the risks that the owner is willing to take with regard to the benefits of keeping the trees in production.

In practice, the term "deadlock" often uses these arguments without actually setting them out. Sometimes even the commercial aspect will suffice, when the diameter and/or quality of the trees are unattractive to the dominant market. **In short, deadlock is a broad concept which currently combines biological and strategic aspects.**

However, we believe that assessing deadlocked areas is essential, in view of the current health status of some stands and the interactions between the dynamics of these stands and ongoing climate changes. For this study, we have adopted this term but defined it more precisely, to differentiate between crisis situations proven or very likely to be linked to high physical or health vulnerability (true deadlock), and situations where the

judgement of deadlock is used to justify a decision to accelerate harvesting and to replace stands by clear-cutting and planting.

In a stricter sense of the term, the "deadlocked" stand should display two characteristics:

(1) compromised health status according to the DSF, i.e. with at least 20% of trees showing over 50% fine dead branches (hardwood) or defoliation (softwood) according to the "Dieback" protocol (Goudet and Nageleisen, 2019);

(2) natural regeneration absent or unable to guarantee a future closed stand reaching at least the dominant height of the site's natural phytosociological mix.

The first condition is essential; if it is met without the second, the wood will be harvested in one or more stages depending on the rate of dieback and the extraction sacrifices incurred, but the stand will not be reforested (which requires careful logging and skidding).

Nevertheless, the DSF threshold of 20% seems too low to us because for some species, trees that are 50% defoliated in certain seasons can be quite resilient. A stand's decline should be defined more precisely by using a method such as "Archi" to assess its resilience capacities (Sajdak, 2019; Drénou and Caraglio, 2019). The physical risk (windfall and windthrow) is difficult to predict and we will consider that it can be absorbed into the health risk, because dieback greatly increases the vulnerability of stands to this factor. If both the first and second conditions are met, the stand is harvested and renewed by planting.

Four situations sometimes described by managers as deadlock have thus been excluded:

(1) coppices deemed "unimprovable" but with enough dynamic stems, which could thus be retained as standards if the process is not drastic (e.g. chestnut);

(2) healthy stands that are considered "not very productive", because they constitute a carbon stock and have landscape, social and ecological value;

(3) accessible stands deemed "over-capitalised" due to late thinning, because they can be worked on with careful thinning;

(4) stands with a majority of diameters too large to be physically sawn (D > 1 m), because they now occupy a negligible surface area.

The main scenario proposed therefore anticipates that only stands doomed to dieback will be replaced through planting. These stands primarily comprise plantations that are now off-site (e.g. spruce), coppice that has been depleted due to repeated cutting (e.g. chestnut), and species in health crisis (ash), and secondarily boundary areas for certain species (beech, pedunculate oak). We recognise that defining whether a species is "off-site" should be based more on the concept of a climate niche (ecological) than a climate envelope (statistical), but this approach would require extensive analysis for each species.

We have used the concept of deadlock only for managed forests, with natural forests being chosen from among the most resilient stands to avoid massive mortality by 2050, even though we allow for a trend of increasing mortality (see Chapter 4). In concrete terms, deadlocked areas have been estimated for each species based on the 2014 foliar deficit figures (IGN, 2015), using the expression [average % of foliar deficit] x [% of trees with more than 60% foliar loss], increasing the rates for species whose situation has been worsening since 1997. We then deduct 25% of the areas obtained, corresponding to the unmanaged areas (section 2.2.3).

For 2019, this first filter gives between 4% and 18% of the area, depending on the main species (high extremes for ash and chestnut, low extremes for pines and common oak), and a total of 946,000 ha or 5.9% of French forest. However, in mixed stands, if a single non-majority species dies back, it would not place the stand in deadlock as long as the others are physically stable. This is the case for mixed stands of chestnut-oak (chestnut is fragile), oak-pine (pedunculate oak is fragile) and fir (spruce is fragile). Moreover, according to the literature, mixed stands are more resilient than pure stands (Chapter 2). Stands considered deadlocked in a strategy

that seeks homogeneous plots (homogeneous even-aged high forest or simple coppice system) would not be considered so in a strategy using diverse diameters and species to overcome crises (continuous cover and conversion with standards): the very vision of the future can be influenced by the silviculture chosen. In this study, for mixed stands we have chosen the strategy of maintaining cover by using existing trees, if their health and physical condition permits. For each species, we have excluded from deadlock a proportion of the area corresponding to mixed stands according to the IFN figures: to deadlocked areas for individual species, we apply a deduction of 20% for softwood and uncountable trees, and 40% for hornbeam, hardwood and miscellaneous softwoods (almost always mixed). It is also assumed that deadlocked stands of holm oak will not be reforested, given the low potential of the corresponding sites. However, we should always consider the risk of pure pockets within mixed stands that could create local deadlock situations, at least temporarily. On the other hand, some areas classified here as deadlocked could nevertheless undergo customised natural regeneration thanks to seed bearers from neighbouring stands. These two effects will be considered to offset each other.

This results in the table presented on the following page. In 2019, the deadlocked areas to be replaced through planting are estimated **at 486,000 ha in total, or 3.0% of French forest**. However, this estimate merits further research, for example for fir, spruce and pedunculate oak. In addition, new deadlocked areas will probably be identified between 2020 and 2050. Thus, in developing our scenarios, at paragraph 3.6.4 we assume a change in total deadlocked area that reflects the mortality rate represented in the climate scenario.

### 3.3.3. Practising continuous cover forestry

We will use the term **"continuous cover forestry"** to refer to an approach that deliberately avoids rupturing the canopy. This approach is defined as "continuous, uneven-aged and close-to-nature silviculture" (*sylviculture irrégulière, continue et proche de la nature* – SICPN in French) (Duchiron, 1994; Bruciamacchie and de Turckheim, 2005; Pro Silva Europe, 2012; Pro Silva France, 2014). It consists of working towards stock that oscillates around an "equilibrium volume", making it possible to then harvest net productivity through "selective cutting". SICPN does not prohibit final cutting (all trees), but limits its area as far as possible, depending on the temperament of the species (shade-loving/sun-loving), the condition of the stand (health, diameters, stability) and the presence of regeneration. Irregularity is not an objective in itself, and may be achieved in smaller or larger units (single-tree, clump, patch). In continuous cover forestry, the harvesting limit is not the variable "triggering renewal of the plot"; rather, it is a factor in spreading the harvest between trees during tagging and a factor in ensuring equilibrium in the volume per hectare. Harvesting is thus decided tree by tree, using multiple criteria combined by the field operator at plot scale (balance of age groups) and tree scale (current and potential value, silvicultural roles). The harvesting limit, defined in diameter and not in age, is certainly a decisive criterion, but it varies according to the site and the quality of the trees.

With the exception of stands in crisis as defined above, it is possible to gradually transform stands into mixed uneven-aged high forests whether they are coppice, high forest, or a mix of coppice and high forest (AFI, 2009). This transformation can take a long time and it seems clear that it will not be completed by 2050, but our strategy plans to extend the process by maintaining forest cover on all areas not considered deadlocked. Thus, the scenarios studied include "continuous cover forestry" characterised by:

– Cessation of the simple coppice system, with conversion to coppice with standards of all coppice not judged to be in deadlock. This objective may seem very ambitious, but it is achievable with strong political will, as it involves applying coppice selection to 30–40,000 ha/yr over the period 2020–2050, through cutting generating 50–100 m$^3$/ha or at least 2 Mm$^3$ a year;

– Composition that does not exclude "exotic" species, but limits their expansion, aiming for a mix of species everywhere and favouring species from the natural vegetation layer, keeping "secondary" species at current low prices (detailed by species below);

– Moderate intensity cutting, minimising shocks to stands and maximising the development of timber, while ensuring fair remuneration for felling and skidding;

**Areas estimated to be in true deadlock in 2019:**

| Species | A-tot | M$_0$ | %A | A-deadlock | A-reforest | Main reasons for dieback (low climate resistance or high pathogen pressure) |
|---|---|---|---|---|---|---|
| Pedunculate oak | 1,661 | 0,30 | 8 | 133 | 80 | Dry sites (low AWC), summer droughts, southern extreme of area, defoliating caterpillars |
| Sessile oak | 1,382 | 0,15 | 5 | 69 | 41 | Dry sites (low AWC), struggling soils, summer droughts, southern extreme of area, defoliating caterpillars |
| Beech | 1,016 | 0,15 | 6 | 61 | 37 | Dry sites (low AWC), low altitude, summer droughts, bark beetles |
| Pubescent oak | 1,009 | 0,30 | 5 | 50 | 30 | Very dry sites (low AWC), low altitude, summer droughts |
| Holm oak | 622 | 0,30 | 4 | 25 | 15 | Very shallow soils, low altitude other than coastal |
| Chestnut | 519 | 1,95 | 12 | 62 | 37 | Coppice on old stumps without standard trees, dry sites, very acidic soils, canker, ink disease |
| Ash | 423 | 0,45 | 14 | 59 | 36 | Majority ash stands in ash dieback zone; low AWC or heatwave outside ash dieback zone |
| Hornbeam | 407 | 0,15 | 4 | 16 | 10 | Dry sites (low AWC), summer droughts, southern extreme of area, dry soils |
| Maritime pine | 805 | 0,30 | 4 | 32 | 26 | Dry (low AWC) and/or very acidic sites, processionary moth, rust |
| Scots pine | 640 | 0,75 | 6 | 38 | 31 | Very dry (low AWC) and/or very acidic sites, processionary moth, rust |
| Norway spruce | 445 | 0,75 | 12 | 53 | 43 | Low AWC and low altitudes, dry soils and southern slopes, heatwaves, summer droughts, bark beetles, fomes |
| Silver fir | 458 | 0,30 | 7 | 32 | 26 | Low AWC sites, low altitudes, heatwaves, summer droughts, mistletoe, fir broom rust, adelges |
| Douglas fir | 322 | 0,45 | 5 | 16 | 13 | Low AWC and low altitude in the south, heatwaves, summer droughts, rust, cambial necrosis |
| Black pine (Aleppo and black) | 275 | 0,45 | 5 | 14 | 11 | Very dry sites (low AWC), low altitude in Mediterranean zone, Sphaeropsis, red band needle blight |
| Secondary hardwoods including birch | 1,373 | 0,45 | 5 | 69 | 34 | Dry and/or impoverished sites, pathogens depending on species |
| Secondary softwoods including larch | 316 | 0,45 | 4 | 13 | 6 | Dry and/or impoverished sites, pathogens depending on species |
| Unidentified | 206 | 0,45 | 4 | 8 | 4 | Dry and/or impoverished sites, pathogens depending on species |
| Uncountable (D < 7.5 cm) | 217 | 0,30 | 4 | 9 | 7 | Dry and/or impoverished sites, pathogens depending on species |
| **Total** | **12,098** | - | - | **760** | **486** | - |

*Key: A-tot = 75% of area in France (managed), in kha; M0 = annual mortality rate 2019 as a % of standing volume (adjusted IFN, see 3.6.3); %A = % of area that is estimated deadlocked; A-deadlock = area estimated to be deadlocked, in kha (see text); A-reforest = area to be reforested, in kha (see text); AWC = available water-holding capacity*

– Definition of an "equilibrium volume of stemwood per hectare", allowing harvesting and continuous renewal of stands (Pro Silva France, 2013);

– Adjustment of harvesting rates to move towards these equilibrium volumes by 2050, with these average rates by species varying according to the context (high or low initial stock);

– Total lack of removal of "smallwood" (D < 7 cm) and stumps;

– Rational harvesting of the total volume of branches, to be adjusted in line with the species to safeguard their biological (biodiversity) and fertilising functions, with a minimum set to enable forestry and extraction work;

– High harvesting limits allowing natural regeneration (sexual and soil maturity) and yet compatible with the processing tools currently available;

– Prioritising natural regeneration, to avoid loss of cover and benefit from genetic capital in terms of quality and climate adaptation (silvicultural selection, epigenetics), while retaining the option to plant in the absence of natural regeneration or for local enrichment without extensive clear-cutting (species for diversification or climate adaptation);

– Keeping some of the dead wood produced annually in the forest, to create natural senescence islands and increase the volume of dead wood in the forest, an essential element for saproxylic biodiversity (threatened), soil fertility and pathogen regulation (resilience to climate change).

## 3.4. Pillar 2: Preserving and increasing carbon stocks in wood products

All French strategies emphasise the role of wood products in climate change mitigation (Roux et al., 2017; MAAF, 2018; MTES, 2018a). As paper is too ephemeral a stock to play a mitigating role, it will be addressed alongside wood energy. To increase carbon storage in **construction** from 2020 to 2050, the following measures will be taken:

– Comply with cascading use (Pro Silva France, 2012a; WWF, 2016) and favour the most long-lasting products: traditional carpentry and joinery for large-diameter wood, solid wood reconstituted with medium wood for large spans, wood-framed structures for small-diameter trees. According to the wood sector diagram presented earlier, pallets and packaging (unsustainable) account for 36% of sawn timber.

– Develop sustainable uses for industrial wood: OSB and MDF with formaldehyde-free glues for pulpwood; poles and posts for small-diameter wood not very prone to contraction and knots.

Sawable softwoods will be recovered up to a small-end diameter of 15 cm and all sawable hardwoods will be recovered as timber up to a small-end diameter of 20–30 cm excluding sapwood, depending on the species, including beech, chestnut and secondary white woods (birch, aspen, hornbeam, lime) without any critical flaws for structural use. The storage spans of the products are given in Chapter 4.

## 3.5. Pillar 3: Substituting with wood and reducing emissions from the sector

While substitution is widely detailed in the current proposals in France, improving displacement factors by reducing "upstream emissions" (extraction-transport-processing) seems to attract little attention, although in recent decades the energy expenditure involved in conveying wood from forest to consumer has been increasing through increased mechanisation and transport. To increase the beneficial effect of the forestry sector, emissions must be minimised by means of the following:

– Low-impact forestry operations: no stump extraction or ploughing, respect for diversity during clearing and thinning, limited tonnage and ground pressure;

- Conveyance of wood that limits transport incurred through taking to market, set-up of the site, felling and skidding (regional companies);

- Mechanised felling reserved for small softwoods with few branches, on gentle slopes (mechanised felling emits around five times more $CO_2$ per m³ than manual felling, excluding emissions generated through manufacture, maintenance and recycling of felling machines);

- Low-impact skidding to preserve soil function and carbon stock;

- Limiting use of wood energy to high-efficiency projects (heat + electricity), locally supplied;

- Sawing at the closest possible facilities and energy-efficient processes.

Wood stocks that can be put to industrial use (pulp for paper/building, logs and poles) or energy use (logs, chips, pellets) are considered interchangeable, at least on a regional scale. Therefore, we are viewing it as a single pool of WIWE (wood harvested for industry or for energy generation), for which use trade-offs are critical and will be studied in Chapter 5. Within the framework of this study, and in line with the assumptions adopted, the pool considered as sustainable WIWE comprises the following:

- Wood resulting from thinning, as part of forestry for quality timber;

- Part of the tip and branches resulting from harvesting of mature trees, excluding the harvesting of smallwood (wood with a diameter of less than 7 cm);

- Wood-processing waste (bark stripping and trimming, sawing, milling, etc.).

# 3.6. Analysis of 2020-2050 scenarios

### 3.6.1. Common basis

For all scenarios, French forests are considered 75% exploitable by 2050 based on an estimated management rate of 65% in 2020 (section 3.2), with a linear progression in this rate between 2020 and 2050 due to equipment and consolidation efforts. Thus 25% are left natural until 2050, which corresponds to the recommendations of Dooley et al. (2018), with 10% prohibited by law in 2050. In 2020, the area of forests classified as deadlocked is 3%, which will evolve by 2050 at a pace determined by the mortality rate used, as explained in points 3.6.3 and 3.6.4.

For all scenarios, management of the three standard contexts is defined by the following characteristics:

| | Natural forest (NF) | Continuous cover forestry (CCF) | Deadlocks (DEA) |
|---|---|---|---|
| **Treatment(s)** | None | Evolution towards mixed uneven-aged high forest (heterogeneous textures depending on species composition) | Harvesting of existing stand, followed by even-aged high forest until 2050 (young plantations) |
| **Evolution in composition \*** | Natural | Maintaining diversity, favouring mixed stand details in Chapter 4 | Renewal with new species – details in Chapter 4 |
| **Type of cutting** | None | Thinning only, with gaps tailored to the species | Clear-cutting of patches max. 2 ha. |

*\* The expected evolution of the respective share per species is detailed in Chapter 4.*
<u>*Increasing:*</u> *sessile, pubescent and holm oaks; maritime, Scots and black pines; Douglas fir, European larch, cedar, secondary hardwoods and Mediterranean species*
<u>*Decreasing:*</u> *pedunculate oak, beech, chestnut, ash, hornbeam, spruce, silver fir.*

In all climate scenarios for France, until at least 2035, increased fertility due to increasing atmospheric $CO_2$ concentration should compensate for the suppressive effects of temperature increases, which should in turn maintain current gross productivity (Colin and Thivolle-Cazat, 2016). As the IPCC (2018) climate scenarios do not differ significantly until after 2050, we have assumed constant biological productivity between 2020 and 2050 for all species, except in deadlocks where it is logically proportional to the residual leaf area. It is possible that the RCP 8.5 climate scenario will reduce gross productivity before 2050, but it seems highly risky to simulate this effect, and the progression in mortality rates applied (see 3.6.3) should cover it.

**Natural forest (NF)**

The first context is forest with no timber extraction. This context does not require a technical definition, apart from the policy choices set out in the main report. The distribution of areas between species was chosen according to four criteria: economic value of standing timber; accessibility (costs of creating access and of exploitation); species-site adaptation (to reduce the risk of accelerated mortality); and ecological value of the corresponding ecosystems including the proportion of large- and very large-diameter trees (carbon value and biodiversity). The distribution is given in the table of pathways below.

Given that one third of the natural forests are located on land that is difficult to exploit and therefore probably on relatively shallow soils, and that there are stands similar to those classified as "deadlocked" (a meaningless term in the case of natural forest), for this approach we have applied a flat-rate reduction of 5% to IFN gross productivity for each stand type.

**Continuous cover forestry (CCF)**

The second context is managed forest, to which we will apply continuous cover forestry as defined in point 3.3.3 of the report. However, this must be adapted for the third context (deadlocks), detailed below.

The table below, summarising the parameters set per species under CCF, has been established as follows:

1) The **composition** evolves according to the table below, in response to the foreseeable health changes in the chosen climate scenario and in relation to the areas in 2019:

   Loss > 10% for: ash, spruce, chestnut, pedunculate oak and silver fir (−11%);
   Gain > 10% for: sessile oak, pubescent and holm oak, black pine and Douglas fir (+11%);
   Changes of between -10% and +10% for other species.
   These changes retain the current ratio between hardwood and softwood.

2) High **harvesting limits** are set, to allow natural regeneration (sexual and soil maturity), but limiting the risk of dieback and remaining compatible with processing tools currently available (Chalayer, 2019).

3) The **equilibrium volume/ha in managed forests** under continuous cover forestry (in m³/ha of stemwood) corresponds to the equilibrium for the main species in uneven-aged high forest (all diameter classes combined), estimated from the basal area standards of the Pro Silva network (Pro Silva France, 2013), and taking into account the harvesting limits set, which gives between 92 m³/ha (holm oak) and 406 m³/ha (Douglas fir). However, these levels are not absolute as they depend on the site. For France, the average equilibrium level would thus be around **205 m³/ha**.

4) **Average rotation**: 5 to 15 years depending on the species and site (increase), compromise between canopy disturbance and soil disturbance.

5) **Annual harvest rate** of net productivity: this is established for each scenario and species according to the principles defined in section 3.6.2.

6) Dead wood from **natural mortality** is harvested at a rate linked to the management scenario (see Chapter 3) with a minimum of 10% for reasons of safety (roadsides and inhabited areas) and traffic for forestry and extraction operations. This means that up to 90% of naturally dead wood decomposes slowly in the forest and thus generates senescence islands that are essential for biodiversity.

7) The **branches** of felled trees are harvested at a rate that depends on the management scenario (see Chapter 3), with a minimum of 20% to allow forestry work and a maximum of 75% considered as the maximum technically feasible with realistic economic cost (50–90%, depending on incline and species).

8) For **renewal**, priority is given to natural regeneration while preserving forest cover as far as possible (rationale in the scenario), with approaches tailored to the behaviour of each species (sun-loving, shade-loving, vertical or lateral light, germination and initial growth, competition).

9) Finally, we considered that the proportion of **timber** in the stemwood given by the IFN for each species (2019) remains constant until 2050 (cautious option), because if diameters and quality are to increase, the strict criteria for improvement thinning in this scenario will preserve future good quality large-diameter wood and medium-diameter wood.

**Evolution of stand types by main species in continuous cover forestry:**

| Main species (% ha) | IFN 2019 | Target 2050 | Evolution |
|---|---|---|---|
| Pedunculate oak | 12.9 | 10.8 | Maintaining oak, while encouraging sessile oaks and keeping secondary species, localised diversified planting |
| Sessile oak | 10.8 | 12.7 | Sessile oak and secondary species favoured over pedunculate oak |
| Beech | 9.0 | 8.2 | Maintaining beech, while encouraging sessile oak and secondary species, thinning with strict health criteria |
| Pubescent oak | 9.0 | 10.0 | Maintaining pubescent oak with secondary species, natural evolution in its favour |
| Holm oak | 4.8 | 5.7 | Maintaining holm oak with secondary species, natural evolution in its favour |
| Chestnut | 4.6 | 4.0 | Maintaining chestnut in mixed stand, coppicing with standards to encourage other species (sessile oak, pubescent oak, pines, etc.) |
| Ash | 4.1 | 3.3 | Maintaining ash in mixed stand, while encouraging other species, and isolating firmly in event of ash dieback (oak, cherry, maple, etc.) |
| Hornbeam | 3.5 | 3.2 | Maintaining hornbeam in mixed stand with other species |
| Maritime pine | 6.5 | 7.1 | Developing maritime pine while encouraging mixed stand (sessile and pubescent oak, birch, rowan, other pines, etc.) |
| Scots pine | 5.5 | 5.8 | Maintaining Scots pine while encouraging mixed stand (sessile and pubescent oak, rowan, maple, birch, fir, etc.) |
| Norway spruce | 3.9 | 3.1 | Maintaining spruce in mixed stand (fir, Douglas fir, beech, sessile oak, pine, maple, etc.) and working towards regeneration |
| Silver fir | 3.6 | 3.2 | Maintaining fir while encouraging mixed stand (beech, Douglas fir, sessile oak, Scots pine, maple, birch, rowan, etc.) |
| Douglas fir | 2.5 | 2.8 | Maintaining Douglas fir while encouraging mixed stand (beech, fir, sessile oaks, Scots pine, maples, cherry, etc.) |
| Black pine (Aleppo and black) | 2.4 | 2.7 | Maintaining black pines while encouraging mixed stand (pubescent oak, Scots pine, cedar, sorb, etc.) |
| Secondary hardwood including birch | 10.7 | 11.0 | Maintaining these species in mixtures in other stands |
| Secondary softwood including larch and cedar | 2.8 | 3.0 | Maintaining these species in mixtures in other stands, encouraging mix in larch plantations |
| Unidentified | 1.7 | 1.7 | Maintaining these species in mixtures in other stands |
| Uncountable (D < 7.5 cm) | 1.7 | 1.7 | Maintaining the species planted, retaining companion species during clearing and thinning |
| **Total** | **100.0%** | **100.0%** | |

The table on the following page gives the areas (kha) by management context for each main species, as well as the average harvesting limits, basal areas, equilibrium volumes and expected renewal methods.

**Areas by context and main species, estimated stock in equilibrium and renewal methods in continuous cover forestry**

| Main species | Total | NF | CCF | DEA | HLa | Be | Ve | Renewal method (excluding complementary planting) |
|---|---|---|---|---|---|---|---|---|
| Pedunculate oak | 2,078 | 417 | 1,587 | 80 | 90 | 16 | 188 | Natural regeneration by shelterwood cutting in patches < 2 ha, localised diversified planting |
| Sessile oak | 1,737 | 355 | 1,351 | 41 | 90 | 17 | 203 | Natural regeneration by shelterwood cutting in patches < 2 ha |
| Beech | 1,444 | 428 | 984 | 37 | 70 | 22 | 230 | Natural regeneration, by single-tree and clumps (< 0.5 ha) |
| Pubescent oak | 1,443 | 434 | 970 | 30 | 50 | 17 | 117 | Natural regeneration by shelterwood cutting in patches < 2 ha |
| Holm oak | 769 | 147 | 605 | 15 | 40 | 15 | 86 | Natural regeneration, by single-tree and clumps (< 0.5 ha) |
| Chestnut | 746 | 227 | 472 | 37 | 50 | 22 | 170 | Natural regeneration of mixed stands, by single-tree and clumps (< 0.5 ha), through creating gaps and under canopy in the case of coppicing with standards |
| Ash | 652 | 229 | 370 | 36 | 60 | 19 | 202 | Natural regeneration of mixed stands, by single-tree and clumps (< 0.5 ha), localised diversified planting |
| Hornbeam | 559 | 152 | 401 | 10 | 50 | 25 | 196 | Natural regeneration of mixed stands, by single-tree and clumps (< 0.5 ha) |
| Maritime pine | 1,050 | 245 | 786 | 26 | 60 | 24 | 240 | Natural regeneration by shelterwood cutting in patches < 2 ha, locally with planting under canopy (cedar, Nordmann fir, maple, etc.) |
| Scots pine | 891 | 251 | 612 | 31 | 60 | 24 | 221 | Natural regeneration by shelterwood cutting in patches < 2 ha, locally with planting under canopy (cedar, Nordmann fir, maple, etc.) |
| Norway spruce | 622 | 177 | 398 | 43 | 60 | 28 | 321 | Natural regeneration of adapted species, diversified planting in clumps (< 0.5 ha unless there is a clear trend towards deadlock) |
| Silver fir | 572 | 114 | 433 | 26 | 70 | 30 | 354 | Natural regeneration by single-tree or clumps (< 0.5 ha), diversification in pockets or "nests" (beech, maple, Douglas fir, cedar, etc.) |
| Douglas fir | 404 | 82 | 309 | 13 | 70 | 32 | 406 | Natural regeneration in clumps and strips, planting pockets of diversity (beech, fir, pine, cedar, maple, etc.) |
| Black pine (Aleppo and black) | 378 | 103 | 258 | 11 | 70 | 24 | 232 | Natural regeneration by shelterwood cutting in patches < 2 ha, locally with planting under canopy (cedar, Nordmann fir, maple, etc.) |
| Secondary hardwood | 1,724 | 351 | 1,350 | 34 | 50 | 24 | 171 | Renewal with main stand |
| Secondary softwood incl larch | 448 | 132 | 310 | 6 | 70 | 25 | 250 | Pathways above depending on species (larch ≠ cedar ≠ others). |
| Unidentified | 273 | 67 | 202 | 4 | 50 | 25 | 173 | Renewal with main stand |
| Non-count (D<7.5cm) | 280 | 63 | 214 | 7 | 60 | 26 | 247 | Not applicable (young stands), thinned with a view to continuous cover forestry (criteria of vitality-quality-diversity, not diameter) |
| **Total** | **16,070** | **3,972** | **11,611** | **486** | | | | |

*Total surface area in 1,000 ha: NF = area of natural forest in 2050; DEA = area in deadlock for health reasons in 2020; CCF = continuous cover forestry (managed forests – deadlocked in 2020); HLa = average harvesting limit in cm: diameter at which all trees are extracted (except those left natural), tailored according to quality, site potential and tree health; Be = basal area at equilibrium in continuous cover forestry in m²/ha; Ve = average volume of stemwood at equilibrium in continuous cover forestry, in m³/ha stemwood (Ve with branch = 1.3–1.7 x V stemwood, depending on species).*

**Deadlocks (DEA)**

Applying the definition given in section 2.3.2, we estimated that in 2019, 3% of French forest is **currently** considered to be in a deadlock situation and therefore needs to be renewed by planting between 2020 and 2050. We postulate the following reforestation plan (with possible mixtures of species). In our scenarios, this current rate is assumed to increase at a pace linked to the mortality rate (RCP 2.6 or worse), defined in section 3.6.3. Areas' species composition is assumed to be constant between 2020 and 2050.

| Species | ha | SOak | PuOak | HOak | HW | PIN | SPR | DOU | LAR | SS | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Pedunculate oak** | 80 | 40 | 20 | | 20 | 20 | | | | | 100 |
| **Sessile oak** | 41 | | 40 | | 10 | 30 | 20 | | | | 100 |
| **Beech** | 37 | 30 | 20 | | 20 | 20 | 10 | | | | 100 |
| **Pubescent oak** | 30 | | | 20 | | 20 | 40 | | | 20 | 100 |
| **Holm oak** | 15 | Spontaneous growth (Aleppo pine, scrubland or maquis, etc.) and pastoralism | | | | | | | | | |
| **Chestnut** | 37 | | 30 | | | 30 | 30 | | | 10 | 100 |
| **Ash** | 36 | 60 | | | 30 | 10 | | | | | 100 |
| **Hornbeam** | 10 | 50 | 10 | | 20 | 20 | | | | | 100 |
| **Maritime pine** | 26 | 10 | 30 | | 10 | 30 | | | | 20 | 100 |
| **Scots pine** | 31 | 10 | 30 | | 10 | 30 | | | | 20 | 100 |
| **Norway spruce** | 43 | 10 | | | 10 | 20 | 20 | 20 | 20 | | 100 |
| **Silver fir** | 26 | 20 | | | 20 | 10 | 20 | 20 | 10 | | 100 |
| **Douglas fir** | 13 | 20 | | | 10 | 20 | 30 | | 10 | 10 | 100 |
| **Black pine (Aleppo and black)** | 11 | | 30 | 10 | 10 | 30 | | | | 20 | 100 |
| **Secondary hardwood** | 34 | 20 | | | 40 | 30 | | | | 10 | 100 |
| **Secondary softwood incl larch** | 6 | | | | 10 | 20 | 20 | 20 | 20 | 10 | 100 |
| **Unidentified** | 4 | | | | 100 | | | | | | 100 |
| **Uncountable (D < 7.5 cm)** | 7 | 10 | | | 10 | 40 | 10 | 20 | 10 | | 100 |
| **Total in 2020 (kha)** | 486 | 94 | 72 | 7 | 77 | 107 | 55 | 16 | 14 | 29 | 471 |
| | | **Hardwood = 250 kha = 53%** | | | | **Softwood = 221 kha = 47%** | | | | | |

*Species key:*
*\* HW = other hardwoods (depending on site): chestnut, beech, sycamore and Norway maple, cherry, lime, poplar, etc.*
*\* PIN = pines (other than original species): maritime, Scots and black (including Salzmann), depending on site.*
*\* SS = southern species: hardwoods and softwoods being trialled in the CNPF/IDF programme Life-FORECCAsT (http://www.foreccast.eu).*

The stock of standing timber generated between 2020 and 2050 through new planting on these deadlocked areas has been estimated from the productivity tables for each species, without thinning (stands too young) and therefore without harvesting.

## 3.6.2. Harvesting levels

For areas classified as deadlocked, annual harvesting of stemwood is expressed as a percentage of the standing overbark volume per hectare. Between 2020 and 2050, this harvesting rate increases with the rise in mortality rate by a factor $a$ greater than 1 ($HSW_n = a \times HSW_{n-1}$) and is calibrated so as to reach a zero volume of stemwood in 2050. In 2050, the deadlocked "stock" from 2020 is therefore reforested. If the national share of deadlocks continues to grow, there will still be a "flow" of deadlocks to address annually. In parallel, the next stand resulting from planting evolves according to the area reforested and an increasing productivity per hectare, reaching in 2050 a level directly linked to the species planted as defined above. The average harvest rate for branches and mortality for all species is set at 75% of standing volume and productivity, to allow for planting under realistic conditions.

For stands classified as continuous cover forestry, the annual harvesting rate is expressed as a percentage of net productivity per hectare. To test the calculation model and compare contrast scenarios, we study three

harvesting approaches for these areas, from priority given to the ecosystem to priority given to the sector and societal needs, or a compromise scenario. The average harvest levels for branches and dead wood were chosen on the basis of an estimate of the minimum required to work safely (10–20%), and the maximum technically feasible given the cost of extracting branches on inclines and with long skidding, estimated at 75% (hardwood: 70% in the mountains, 90% in the plains; softwood: 30% in the mountains, 70% in the plains).

All scenarios involving harvesting start from a total harvest in 2020 of 60 Mm³/yr (current level), and the stem-wood harvesting rate is determined by the objectives set in the scenario. The evolution of stocks and flows is then estimated using a "PHM" calculator (production/harvest/mortality) and parameters that have been studied and clearly defined, as described in Chapter 4.

| Scenario | Overall objective | Resulting harvest rates |
|---|---|---|
| Ecos | Reach equilibrium volumes* in 2050, with lowest possible harvesting of branches and dead wood (priority stocks, fertility and biodiversity). | Branches: fixed rate of 20% of the cut; Dead wood: fixed rate of 10% of mortality; Live stemwood: variable rate calculated to reach equilibrium volume in 2050 through linear progression from 2020 (without overall harvesting target). |
| R60 | Approach equilibrium volumes, with stable overall harvesting level of 60 Mm³/yr between 2020 and 2050 and a moderate harvest of branches and dead wood (compromise scenario). | Branches: fixed rate of 50% of the cut; Dead wood: fixed rate of 20% of mortality; Live stemwood: variable rate calculated to harvest 60 Mm³/yr from 2020 to 2050, by harvesting 50% of volume of branches and 20% of dead wood. |
| R95 | Harvest the maximum technically feasible amount of branches and dead wood to reach an overall harvest of 95 Mm³/yr in 2050 (priority economy). | Branches: fixed rate of 75% of the cut; Dead wood: fixed rate of 75% of mortality; Live stemwood: variable rate calculated to achieve linear progression of total harvest from 60 Mm³/yr in 2020 to 95 Mm³/yr in 2050. |

*The equilibrium volumes used for stemwood (in m³/ha) are given in section 3.6.1.*

Harvesting root systems has highly unfavourable results and will therefore be excluded from all scenarios (energy expenditure, loss of carbon, breakdown of the soil and its biological and water functions, etc.).

For each scenario, we first simulate the overall evolution of stocks and harvests based on average parameters for French forests, given by the IFN or calculated from the parameters for each species (Chapter 4) and standing volume representation of this species in French forest between 2020 and 2050, taking into account the evolution projected in the scenario.

Then, to establish the evolution of stocks and harvests for each species, the same calculation model is applied to each species, using its own parameters (Chapter 4) and with the same harvesting curve for 2020–2050, calibrated using an average rate for 2020–2050 that allows the overall harvest to be broken down according to the gap between current and equilibrium volume/ha but also in light of current verified health crises; only those species in health crisis have a rate exceeding 100%.

In summing up the results obtained, we then verify that the total calculated using this "species" input agrees with the values obtained using the "French forest" input and, if necessary, we can revisit the average harvest rate for each species.

These two methods thus enable us to differentiate between two aspects to be decided: the overall strategy for France, and the way it is broken down by species. Regional-scale simulations would enable us to determine on a more appropriate scale the equilibrium volume/ha and harvesting limits for each species. Thus, this approach could enable us to compare the national strategy (top-down approach) with the combination of regional strategies (bottom-up approach), to attain coordination between the two.

However, the protocol adopted does not enable us to simulate harvesting by diameter, which potentially leads to a fairly large margin of error for the products generated. In SICPN-type silviculture (continuous cover), it is

difficult to distribute harvesting by diameter because cutting is not triggered by a harvesting limit applied at the plot level, as explained in the definition of continuous cover forestry in section 3.3.3.
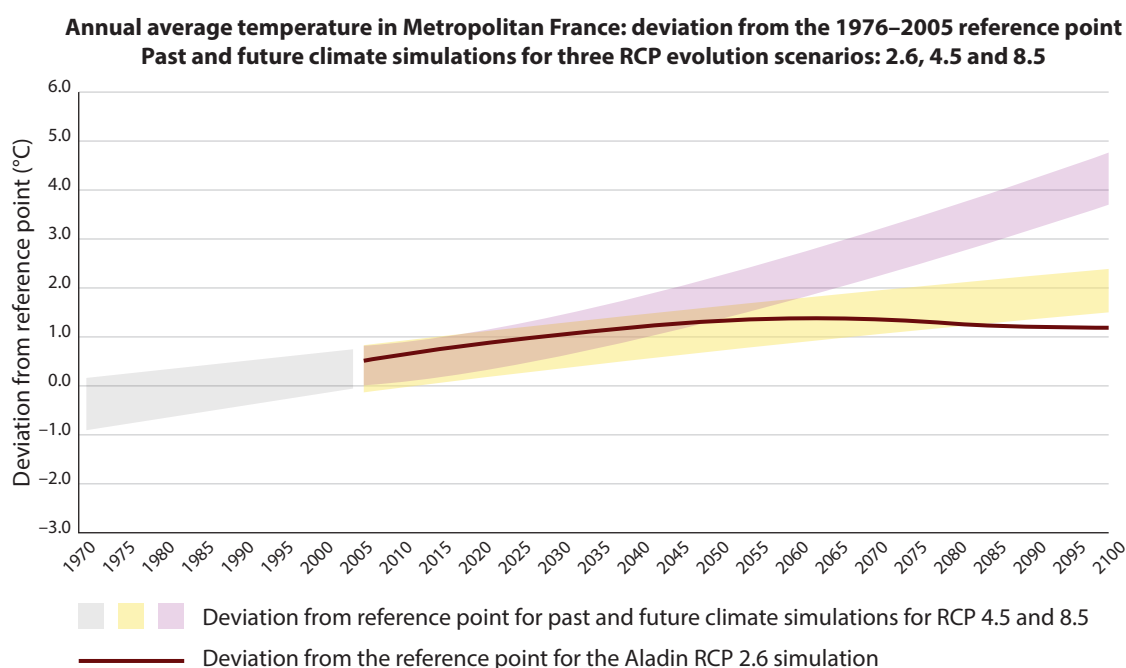
### 3.6.3. Mortality rate

Tree mortality depends on many factors, including climate characteristics and management applied to the stand (see Chapter 2). It strongly influences the evolution of living biomass stocks, as well as that of dead biomass, depending on the decomposition rate of dead wood (see Chapter 4). Its progression between 2020 and 2050 could affect the outcomes of management scenarios (Roux et al., 2017).

The mortality rate is expressed as a percentage of the standing volume. It provides a stock renewal rate, and is thus the inverse of the average lifetime of trees. The average rate given by the IFN (2019) of 0.3% per year corresponds to an average tree lifetime of 333 years. If this rate remains constant and the harvesting rate is low, it would lead in the long term to very high volumes per hectare (see Chapter 4). This mortality rate reflects the young age of trees in French forests, but it is most certainly distorted by current forestry, one of the major characteristics of which is to harvest trees before mortality and to remove most dead trees (therefore not recorded by the IFN). In addition, the IFN figures are based on observation campaigns in 2013–2017, while in recent years mortality has increased, for example in spruce (Mélières and Riou-Nivert, 2019). The true current rates must therefore be higher. As the majority of the areas classified as natural forest are already not being exploited, we will increase the initial mortality rate more for this context. For all species, we apply a flat-rate factor of 1.5 in Continuous Cover Forestry, 2.0 in Natural Forest and 4.0 in Deadlocks. These are assumptions common to all the scenarios studied and can be revised.

In a stand that is not yet mature, mortality evolves exponentially, reflecting increasing competition between stems, before stabilising once the stand is "mature". With the growth in standing volume, a standing volume mortality rate would incorporate the effects of competition, but not the effects of variations in pressure from abiotic agents (climate) and biotic agents (pathogens).

This study focuses on the 2020–2050 period, during which there are no great contrasts between the potential progression in average temperature (see graph below), or the likely effects of these changes on terrestrial ecosystems (IPCC, 2018).



**Annual average temperature in Metropolitan France: deviation from the 1976–2005 reference point
Past and future climate simulations for three RCP evolution scenarios: 2.6, 4.5 and 8.5**

Deviation from reference point for past and future climate simulations for RCP 4.5 and 8.5

Deviation from the reference point for the Aladin RCP 2.6 simulation

Despite the droughts of 2003–2005 and 2015–2017, the "DSF health thermometer" 1998–2017 (DSF, 2018) does not show a general upward trend in the main biotic and abiotic impacts. However, since 2015 the evolution shows a worrying trend, with an average global increase of 0.2°C between 2015 and 2018 (WMO, 2019). Even in the climate scenario RCP 2.6, between 2020 and 2050 we should expect an increase in the frequency of droughts and heatwaves (IPCC, 2018; Mélières and Riou-Nivert, 2019), which would also increase pressure from pathogens (Mélières and Riou-Nivert, 2019), thus causing an increase in mortality.

In practice, simulating the effect of climate change on trees would require a complex and multi-parameter eco-physiological model beyond the means allocated to this study. We use the exponential function described above for competition, to incorporate the gradual increase in the probability of drought and heatwave episodes resulting in mortality. We thus postulate that the mortality rate will progress according to a multiplying factor $a$ greater than 1, as follows: $M_n = a \times M_{n-1}$. This expression gives an exponential progression in M, reflecting the feedback effects of climate on stands, so it is obvious that it can only be applied for a short period of time. If the temperature stabilises in 2050 (scenario 2.6 above), this rate should also stabilise.

We thus define two rates of progression for mortality (M1 and M2) via a factor $a$, variations between species being expressed through the initial mortality rate and the percentage of surface area in a deadlock situation. The steep progression (M2) could correspond to the worsening climate scenario RCP 8.5. For deadlock areas, the progression in mortality leads to an increase in surface area in deadlock between 2020 and 2050, as explained in section 3.6.4 below.

| Parameter 2020–2050 | | Natural forest (NF) | Continuous cover forestry (CCF) | Deadlocks (DEA) |
|---|---|---|---|---|
| Initial mortality rate | | IFN rate (2019) x 2.0 | IFN rate (2019) x 1.5 | IFN (2019) x 4.0 |
| Progression in mortality rate | M1 | +1.5% per year ($a$ = 1.015) | +1.0% per year ($a$ = 1.010) | +3.0% per year ($a$ = 1.030) |
| | M2 | +4.5% per year ($a$ = 1.045) | +3.0% per year ($a$ = 1.030) | +9.0% per year ($a$ =1.090) |
| Percentage deadlock | | 2020 = 4.5% of managed forests; 2050 = 5.0% in M1, 9.0% in M2. | | |

Using this table in calculations gives the following progressions:



Evolution of mortality rates in France (%LB per year)
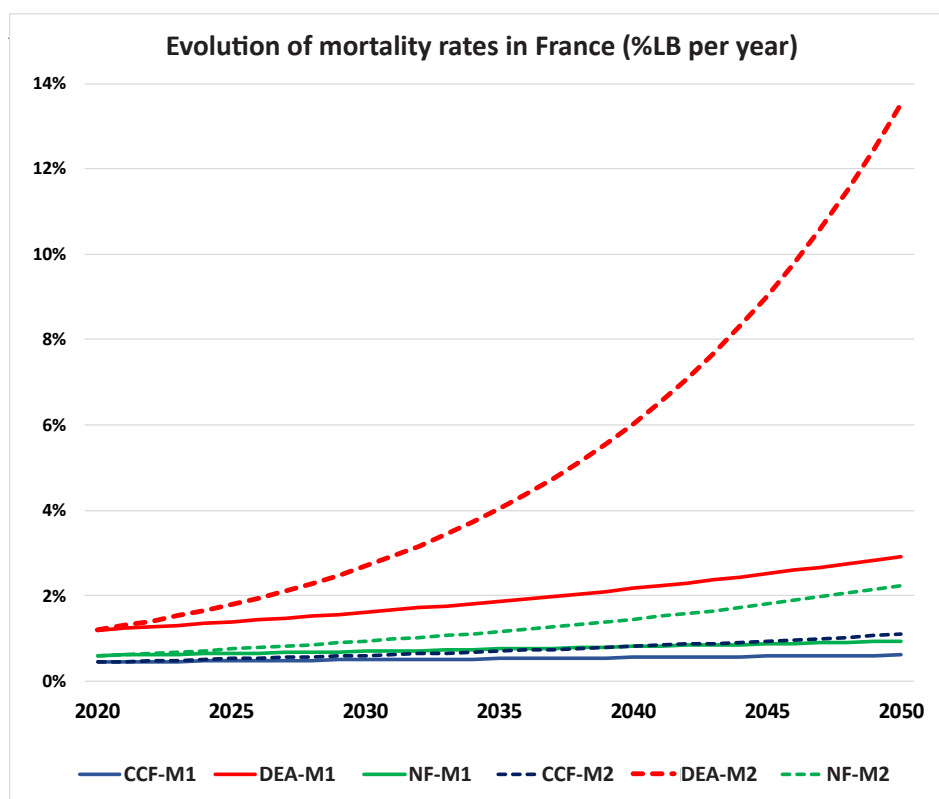
This assumption of overall growth in mortality rates is based on the idea that, regardless of climate change, French forests (which are generally relatively young) are now entering the strong competition phase in forest dynamics, characterised by an increase in mortality rates. The worsening climate scenario RCP 8.5 therefore makes the difference between modalities M1 and M2, with high mortality rates in 2050, especially in deadlocks already characterised by critical health status in 2020.

### 3.6.4. Evolution of areas by management context

In order to calculate the harvesting rates corresponding to the different scenarios, we need to calculate the area involved under each management context, from the current situation until 2050. As explained in Chapter 3.2, we have assumed linear progression in the area under active management, from 65% (estimated current level) to 75% (simulated 2050 level), with the rest of the area (i.e. 35% in 2020 and 25% in 2050) being left natural (no harvesting).

According to paragraph 3.3.2, in 2020 the estimated manageable areas in deadlock represent 0.47 Mha or 3.0% of French forest and 4.5% of managed forest. We chose areas in identical deadlock for the three harvesting scenarios, to test the effect of harvesting rates without effects from other variables. With drought and heat-wave episodes, the proportion of deadlock areas is expected to increase: slightly in modality M1 and significantly in modality M2. In both cases, we assume exponential progression reflecting the mortality rate, giving 2050 levels of 5% with M1 (4% of French forests) and 9% with M2 (7%), as shown in the graphs below.
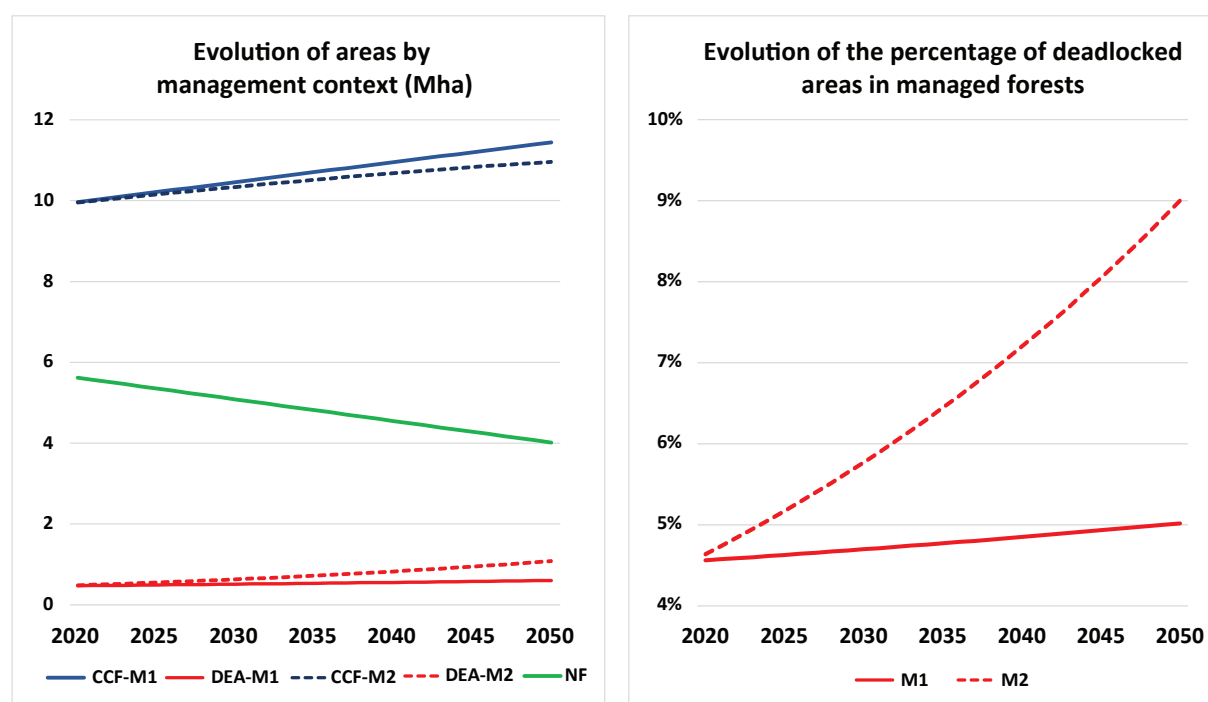


The green curve in the graph on the left shows the areas not affected by regular harvesting; thus in 2020 the term "natural forest" refers to a de facto situation and not necessarily a legal status or a management decision. However, the area represented by this type in 2050, i.e. 25% of French forest, is a strategic choice under the management scenario as explained in 3.6.1.

The steep progression in the percentage of deadlock areas in M2 is a direct reflection of the rapid progression in the mortality rate.

This change in surface areas is included in the calculation of total stocks for French forests.

# 4. CALCULATION METHODOLOGY

## 4.1. Context, scope and baseline data

The study was carried out on a constant surface area of 16.07 Mha, equivalent to the forested area of Metropolitan France in 2018, including Corsica and poplar trees.

Given that the objective is to respect the direction of COP21 and the different climate trajectories of the Intergovernmental Panel on Climate Change (IPCC), especially after 2050, this study assumes the Representative Concentration Pathway (RCP) 2.6 climate scenario, which is characterised by a moderate impact on terrestrial ecosystems (IPCC, 2018). Predicting the role of forests beyond 2050 is particularly uncertain. However, given the risk of runaway climate change beyond 2050 if the necessary efforts are not made, we will also simulate the effects of the higher mortality rates associated with RCP 8.5 climate change.

To study the impact of management scenarios on carbon flows, the most appropriate course of action would be to model trends in forests and products by stand type – a physical baseline factor that encompasses ecological (biotope and dynamics) and historical (past impacts and current and future management) dimensions. To produce and study these scenarios freely, ideally we would be to be able to simulate changes in these stands and their products using a complete national carbon calculator powered by reliable and complete data on the make-up and dynamics of forest ecosystems by linking stations to stands. The most astute pairing would be (1) for the station, the forest ecoregion sub-divided by altitude, geology and topography and (2) for the stand, units defined by combining system, composition and structure criteria (i.e. diameters/age). This approach would allow for the integration of functional linkages between species that could boost forest resilience and therefore be critical in the future, as explained in Chapter 2. However, it was necessary to adapt this ideal to the reality, as explained below.

We worked with data from the National Forest Inventory (IFN), i.e. 33,000 plots for Metropolitan France. However, using these raw data to create a complete, unified and reliable database that met the needs of the study would have required a significant amount of specialist work, which was not feasible within the allocated time and budget. We therefore chose to work with the IFN data published since 2014 and data for 2019 retrieved in "expert" mode via the IFN website. However, these data often do not provide the necessary cross-referencing and overlapping (e.g. structure by composition type for an IFN Large Ecological Region, also known as a "GRECO"). Furthermore, there are occasionally differences between GRECO and national overviews. It was therefore necessary to seek a compromise between using homogenous physical units as a basis for the calculation, and the availability and reliability of data on these units. The national figures were ultimately chosen for their greater stability, by combining the adapted variables with their confidence intervals. To build the database, we reconciled data from several IFN reports and targeted retrievals.

Owing to the diverse nature of the possible characteristics, there is no overarching national type that encompasses the origin, structure and composition of stands as ecosystems (habitats); the only "composition" criterion is already represented by 40 modes, which do not make certain essential distinctions (for example between oaks, other than sessile and pedunculate oaks) for which reliable data on many variables would be difficult to obtain. Additionally, using stand types would make the calculation of harvested products very complex.

Therefore, even if the approach was based on ecosystem ecology and not autecology, it seemed essential to base our estimates on data by stand, defined by its main species, and related to hectarage where applicable. This choice makes it possible to gather the essential information from different IFN sources (areas and volumes, diameters, production and mortality, harvesting, products, etc.).

The main data concern countable trees (D>7.5cm). Plots were deemed to be countable stands if the countable stratum covered at least 10%. As a result, this category may include open stands that are regenerating (e.g. oak groves that have undergone secondary cutting). It was necessary to add an "uncountable" line to those categorised by species, consisting of areas where trees do not exceed 7.5cm in diameter, that is, 280,000 ha of plantations less than 5 years old (63%), 5 to 10 years old (34%) and 10 to 15 years old (3%), depending on the species.

Unlike the method adopted by the IGN, we have chosen to deal with black pines separately rather than under "other softwoods" because they may constitute an important resource in the future and they currently occupy a total of 2.4% of French forested areas, almost as much as the Douglas fir. However, this choice required gathering information that was sometimes difficult to obtain.

We were therefore able to build a comprehensive database based on IFN data published from 2014 to 2019, based on measurements taken between 2009 and 2018.

## 4.2. Calculating changes in stocks between 2020 and 2050

### 4.2.1. Basic principles

The general curve for standing stocks and the carbon cycle was presented in Chapter 2. A production/harvest/mortality (PHM) growth model was constructed to estimate the store changes in the carbon cycle pools for each situation.

Variations in atmospheric carbon resulting from a given forestry sector strategy are referred to as "net emissions", which can be positive or negative (sinks). Over the period covered by this report, 2020–2050, by applying the conservation principle, these emissions can be calculated by adding together the variations in carbon stocks in the different pools influenced by this sector (FAO, 2014; Federici et al., 2015), calculated using inputs and outputs:

| Pool | Carbon input | Carbon output |
|------|--------------|---------------|
| Living tree biomass (LB) | Primary production | Mortality and harvesting |
| Dead wood (DW) | LB mortality | Decomposition of DW |
| Soil carbon (SC) | DW integration | Respiration/mineralisation |
| Wood products (WP) | Supply of sustainable wood products | WP combustion (end of life) |
| Fossil stocks (FS) | Negligible over 30 years | Sectoral emissions* |

*Combustion emissions from fossil fuels used to transport, process and recycle products.*

Thus:     Net emissions generated over the 2020–2050 period = $\Delta LB + \Delta DW + \Delta SC + \Delta WP + \Delta FS$

With:     $\Delta LB = \Sigma_{2020\text{-}2050} (\text{Production}_{LB} - \text{Harvesting}_{LB} - \text{Mortality}_{LB})$
$\Delta DW = \Sigma_{2020\text{-}2050} (\text{Mortality}_{LB} - \text{Harvesting}_{DW} - \text{Decomposition}_{DW})$
$\Delta SC = \Sigma_{2020\text{-}2050} (\text{Integration}_{s} - \text{Respiration/Mineralisation}_{s})$
$\Delta WP = \Sigma_{2020\text{-}2050} (\text{Supply of sustainable WP} - \text{Combustion}_{WP})$
$\Delta FS = \Sigma_{2020\text{-}2050} (Q_{wood} \times DP)$     where DP = product displacement factor ($tCO_2/m^3$).

In view of the available data and resources, we have chosen an empirical (statistical), rather than mechanistic (eco-physiological), approach. Indeed, the literature shows that constructing the ideal calculator mentioned above would require the creation of fairly complex models and sub-models, the parameters of which are all

the subject of research and debate. Whether or not they integrate forest management, models that simulate the functioning and dynamics of forest ecosystems are under development (Dufrêne et al., 2005; Morin et al., 2018), but their use for predictive purposes is now at the forefront of research. Relatively simple statistical calculators have recently been developed for a given plot (CNPF, 2017; Gleizes and Martel, 2019) and allow for highly visual diagrams of changes in carbon stores in above-ground biomass and products. However, the calculators are much more complex for a diversified set of stands with a range of types of forestry.

To carry out the prospective calculations, we drew on several methods: IFN 2005, Gleizes 2017, Roux et al. 2017, EFESE 2017, Valade et al. 2017, Leturcq 2018. A PHM model was constructed to simulate stores and flows for all pools in a hectare of stand, defined by its main species. The results were then imported into Excel sheets to gather and display the values according to management situation.

## 4.2.2. Living biomass

The IFN inventories trees with a diameter exceeding 7.5cm (others are classed as "uncountable") and calculates the volume of "stemwood" (SW), excluding branches and stumps. However, the living biomass of trees includes stemwood, branches and roots, and is therefore estimated as follows:

$$LB = B_{sw} \times (1 + Ec_{br} + Ec_{ro})$$

Where:   $Ec_{br}$, $Ec_{ro}$ = expansion coefficients for branches (br) and roots (ro), defined here to simplify

the calculator, as: $Ec_{br} = \dfrac{B_{br}}{B_{sw}}$ ; $EC_{ro} = \dfrac{B_{ro}}{B_{sw}}$.

Expansion coefficients (branches, roots) are in themselves the subject of debate given the influential factors (such as species and processing). For this study, we have used the average values from Lousteau et al. (2010) and CNPF (2017) for hardwood and softwood.

Like any biological population, from a non-forested setting and in a constant environment, woody biomass follows an exponential curve increasing to an inflection point (maximum current increase), then tends asymptotically towards a maximum (Zeide, 1993). Thus biomass gradually approaches a maximum where production is offset by mortality. In closed-canopy forests, if production and harvesting are constant, changes in the volume can be written as follows:

$$\frac{\partial LB}{\partial n} = P - H - M \qquad \text{where:} \qquad$$

LB = living wood volume (m³/ha); n = year;
P = organic production in year n (m³/ha/year)
H = harvesting + operating losses in year n (m³/ha/year)
M = annual biomass mortality (m³/ha/year)

The solution to this differential equation is exponential and gives the change in the volume of biomass over time after the maximum current increase (Leturcq, 2018). If the mortality rate in % of LB is constant, it can be characterised by a regeneration constant for the standing volume such that $M = \dfrac{1}{T}$, and solving the differential equation gives:

$$LB_n = LB_o \times \exp(-\frac{n}{T}) + T \times (P - H) \times [1 - \exp(-\frac{n}{T})] \quad \text{where} \quad LB_o = \text{initial volume}$$

This expression gives the asymptotic increasing curve set out in Chapter 2.1. T represents the rapid change in the standing capital towards its asymptotic value T(P-H). Because $T = \dfrac{1}{M}$, mortality, M, directly influences the maximum standing capital ($LB_{max}$) and the time required to reach this capital. Thus, for a given output (species/station), the lower the harvesting and mortality, the higher the maximum volume reached. This expression allows us to calculate the volume of timber at any age of the stand (n) once the canopy is closed.

To reflect the probable variation in the mortality rate, we will calculate the volume change by annual recurrence, rather than using the exponential formula, both of which evidently give the same result.

If: $P_n$ = gross stemwood production in year n (m³/ha/year)

Then: $NP_n = P_n - M_n \times SW_n$ = net stemwood production in year n (m³/ha/year)

And from one year to the next (n-1 to n), the **standing volume of timber (m³/ha) evolves as follows**:

$$SW_n = SW_{n-1} + NP_n \times (1 - HSW)$$

With: $HSW_n$ = stemwood harvesting rate (%), according to management scenario.

$$M_n = \text{mortality rate for year n} = \frac{\text{dead volume}}{LB_{n-1}} \, (\%)$$

In Chapter 3, the initial values of M for each species, as well as their annual change, were defined by the "a" factor.

Finally, to calculate changes in **above-ground biomass volume** we used the following formula:

$$LB_n = SW_n \times (1 + Ec_{br} + Ec_{ro}) - Hbr \times NP_n \times Ec_{br}$$

With: Hbr = harvest rate of cut branches (%), constant in the management scenario.
$LB_o$ (LB in 2020), and $M_o$ (M in 2020) are provided by IFN (2019a).
According to IFN (2019a), P is assumed constant, as explained below.

Hbr can be very variable depending on the situation (slope, skidding distances), wood, possible outlets and silvicultural choices, as explained in section 3.6.2.

## 4.2.3. Dead biomass and operating losses

Dead wood comprises stemwood, branches and roots. IFN inventories standing and windfallen dead stemwood, and stemwood and branches on the ground (IFN, 2012b). Dead stumps are not taken into account. In 2012 and 2014 the average value for France was 8 m³/ha (IFN, 2012b; IFN, 2014). A change of method was then introduced to include dead wood of all ages, not just that under 5 years, so that by 2018 the average total dead wood load was 23 m³/ha (IFN, 2019a). While the 2018 values seem high to us, we have retained them for the initial stock by species, considering that it includes all above-ground dead wood, regardless of diameter, age or condition. This average value certainly encompasses very high local variation, including within a stand type, in line with the level of plot management.

The volume of above-ground (ADW) and below-ground (BDW) dead wood decomposes gradually in a forest, so it is calculated as follows starting in year n = 1 where $DW_o$ is given by the IFN (2019a):

$$ADW_n = [ADW_{n-1} + M_n \times SW_{n-1} \times (1 + Ecbr \times (1-Hbr)) + OLa] \times (1 - \frac{1}{DT})$$

$$BDW_n = (BDW_{n-1} + M_n \times BDW_{n-1} + OLro) \times (1 - \frac{1}{DT})$$

Where: DT = average decomposition time for dead wood in the forest = $\frac{\text{half-life}}{\ln(2)}$ (years).

and OL = above-ground (OLa) and root (OLro) operating losses, in m³/lost ha.

For accuracy, DT should be differentiated for branches, stemwood and roots, both for natural dead wood and for operating losses, but the literature does not do so and this distinction would probably have little effect over 30 years. For the 2020 level and below-ground dead wood, in the absence of data, we have assumed that it is equal to half of the total above-ground dead wood volume provided by the IFN.

Roux et al. (2017) provide the half-lives of dead wood for managed forests by listing the average product lifetime (PL): 43.3 years for hardwood with a diameter larger than 7cm, 14,4 years for softwood with a diameter

larger than 7cm and 7.2 years for softwood and hardwood with a diameter less than 7cm. These PL values are modelled according to the diameter of deadwood present. Using the harvest levels to estimate the amount of dead wood with a diameter above or below 7cm, gives the following averages:

| Situation | NF | Continuous cover forestry | | | Deadlocks |
|---|---|---|---|---|---|
| | | Ecos | R60 | R95 | |
| Volume D>7cm / Volume D<7cm | 4 | 3 | 1,5 | 0,5 | 0,5 |
| Hardwood | 36 | 34 | 29 | 19 | 19 |
| Softwood | 13 | 12 | 11 | 10 | 10 |

We model the averages by species as indicated, for example in scenario R60 in the parameter table in section 4.2.9. It should also be noted that some dead wood is reabsorbed back into the ground, thereby increasing the life of the stored carbon. However, this storage gain should be considered as part of the annual soil storage presented below, at least for managed forests in continuous cover forestry, since the estimation is based on plots managed by the National Network for Long-term Forest Ecosystem Monitoring (RENECOFOR) and with forest canopies.

**Operating losses** include sawdust, fallen bark and all dead wood that is cut and not harvested. They are currently poorly documented and therefore difficult to estimate, as they depend on the details of the products removed and the chances of root survival through anastomosis and stump regrowth. To distinguish between above-ground dead wood (a) and below-ground dead wood (b) and the associated losses (OLa and OLro), these pools are calculated separately using the following formulae ($m^3$/ha):

$$OLa = HSW \times NP_n \times Ec_{br} \times (1 - Hbr)$$
$$OLro = HSW \times NP_n \times Ec_{ro} \times M_{ro} \text{ (without stump harvesting).}$$

Where:   $M_{ro}$ = root mortality rate after cutting (%).

The $M_{ro}$ factor seems to be very poorly documented. For this study, 30% continuous cover forestry (thinning) and 10% deadlock (clear-cutting) will be used. These figures should be refined, but literature on the subject is lacking. Some of the carbon from dead roots is absorbed into the soil rather than being released into the atmosphere, but this factor will be treated (as explained above) as dead wood in general. It should be noted that an error involving the $M_{ro}$ factor would have relatively limited consequences.

## 4.2.4. Soil carbon

While this pool is essential, estimates differ: in France, it may represent on average 300 $tCO_2$eq/ha in the first metre (Jonard et al., 2019; Derrien, 2018) and 610 $tCO_2$eq/ha in total (Martel et al., 2017 in EFESE, 2019), or an average of 1.32 times the carbon in biomass (Dupouey et al., 2000). In the first metre, the carbon stock is thought to be 50% in the surface horizon (0–30cm), with an average residence time of 30 years at 10cm and 300 years at 40cm (Derrien, 2018). If storage beyond 1m is significant, it is considered very stable.

The forest soils of France continue to act as sinks (Jonard et al., 2019), but the flows by stand type are difficult to establish. Silvicultural practices, particularly in deadlocks (where soil is exposed), could reduce this capacity, at least temporarily. However, in theory carbon storage should reach an upper limit when the storage of the wood volume reaches a maximum, as explained above. It will therefore evolve according to the following equation:

$$SC_n = SC_o \times \exp(-\frac{n}{T}) + Ts \times As \times [1 - \exp(-\frac{n}{T})]$$

Where:   $SC_o$ = initial storage; Ts = C-soil regeneration constant
        As = gross annual storage.

While it is possible to approximate $SC_o$, it is very difficult to determine the overall residence time of carbon in soil (Ts), which is likely to be high, along with the gross annual storage (As). These uncertainties make it difficult to use the above formula. There are annual storage differences according to species, stand and practices, but these are poorly documented. As the 2020–2050 period is very short for soil, the matter of carbon storage in the first metre will be approached by using the cumulative average net annual storage of 1.28 tCO$_2$eq/ha until 2050 (Jonard et al., 2019). It is possible that this annual storage is higher in forests left to grow freely thanks to the supply of dead wood and the more measured microclimate. Nevertheless, this pool is important in terms of storage, but its potential variation is relatively small over 30 years, so an error should have a limited effect. On the other hand, for the 2050–2100 period studied in section 5.2.5, annual storage will be reduced by 2% each year, resulting in a value of 0.47 tCO$_2$eq/ha in 2100 (and 0.17 tCO$_2$eq/ha in 2200 for the long-term unmanaged perspective studied for natural forests).

## 4.2.5. Harvesting

The total volumes of harvested wood are the result of the harvesting options defined above, that is:
- the harvesting rate of stemwood;
- the harvesting rate of branches (above-ground biomass excluding the main stem);
- the harvesting rate of naturally occurring dead biomass;
- the harvesting rate of roots (zero);
- the proportion of timber from stem;
- the rate of panels and logs/posts/stakes created from wood harvested for industry or for energy generation.

This gives the harvests for year n:

Harvest stemwood (n) = $NP_n \times HSW$
Branch harvest (n) = $Hbr \times HSW \times Ec_{br}$
Dead trees harvest (n) = $H_M \times M_n \times SW_{n-1} \times (1 + Ec_{br})$*

→ Total harvest (n) = Stemwood harvest (n) + Branch harvest (n) + Dead tree harvest (n)

Timber harvest (n) = $HSW \times \%TIM \times \%R_{TIM}$ *
Wood harvested for industry or for energy generation (WIWE) = Total harvest (n) – TIM harvest (n)
Wood harvested for panels for use in industry (n) = 0.10 × wood harvested for industry or for energy generation (n)*
Wood harvested for logs/posts/stakes for use in industry = 0.02 × wood harvested for industry or for energy generation (n)*
Wood harvested for industry or for energy generation (WIWE) paper harvest = 0.18 x WIWE harvest (n)*

→ Wood harvested for energy generation (wood energy) = wood harvested for industry or for energy generation – wood harvested for panels for use in industry – wood harvested for logs/posts/stakes for use in industry – paper

* According to FCBA figures (2018), and where:
HM ($R_m$) = harvest rate of naturally dead trees (%);
%TIM (BO) = timber share of stemwood estimated in the field by IFN (2019a);
%RTIM = actual recovery rate of timber, set here at 80% to limit waste as much as possible (if the current reality is 75%, this assumes a change from 75% in 2020 to 85% in 2050).

For WIWE, there are of course "round wood" volumes, which differ from the product volumes consisting of processing waste or recycled wood. We recall that in our main scenario, all wood harvested for industry or for energy generation comes from thinning, apart from clear-cutting carried out in deadlocks according to the criteria defined above.

## 4.2.6. Storage of wood products

Timber (TIM) consists exclusively of sawable wood, while wood harvested for industry or for energy generation refers to wood that can be used as pulpwood (paper, energy, panels) or for logs, posts and stakes, which are generally interchangeable outlets. In the pool that comprises wood harvested for industry or for energy generation, wood harvested for energy generation and paper has an average lifetime of 1 year (CNPF, 2017) so its stocks are not taken into account. Sawable timber and wood for industry to be used in panels and posts, on the other hand, constitute relatively sustainable carbon stocks. If PL is the lifetime of the products, the storage of wood products in 2050 (WP) for each product changes year on year, according to the following formula:

$$WP_n = (WP_n\text{-}1 + P \times \text{H-TIM}_n) \times (1 - \frac{1}{PL})$$

Where:   $\text{H-TIM}_n$   = processed wood products for year n (m³/ha) = see section 4.2.5.

P        = product processing yield (%).

PL       = average product lifetime = $\frac{\text{half-life}}{\ln(2)}$.

The products' initial stocks ($Pb_0$) for Metropolitan France are taken from Roux et al. (2017): 322 m³ for timber, 74 Mm³ for panels and 12 Mm³ for logs, posts and stakes.

Of course, the lower the PL is, the faster the carbon stock reaches its limit.

According to FCBA, in 2018, the volume stored in panels, logs and posts, i.e. 8 Mm³/year, is the result of a triple supply, with WIWE (round wood) accounting for 50%, TIM (processing waste) for 30% and recycled wood (end-of-life TIM) for 20%. We have therefore reincorporated the corresponding portion of processing waste and end-of-life timber into the sustainable wood for industry (WI) stock.

The products' lifetime (PL) is assumed to be constant for the 2020–2050 period. CNPF (2017) recommends an average half-life of 35 years for timber and 25 years for panels, which corresponds to 50 and 36 years respectively. However, for timber, we must bear in mind that 36% of sawn timber (pallets and packaging) has a very low lifetime. The PL is therefore set at 40 years for timber and 30 years for sustainable wood for industry (36 years for panels and 10 years for logs, posts and stakes).

For products' first and second processing yields (P):

–   For timber, depending on the species and quality, the average yield for first processing is 41% to 58% (FCBA, 2018), and we have used an average of 50%. Losses from secondary processing (which are burnt) are sometimes not considered in the analyses (Roux et al., 2017) but are nevertheless significant. Indeed, for timber, secondary processing adds up to 50% of volume losses for stave wood according to FCBA (2018), with lower losses in construction. For softwood, the proportion used for joinery/furniture is lower. For timber, we will therefore use a secondary processing yield of 70% for hardwood and 90% for softwood, giving a total of $P_{\text{TIM}}$ = 40% hardwood and 45% softwood.

–   For panels and logs, stakes and posts, an overall yield of 90% will be used.

## 4.2.7. Displacement and emissions in the sector

Estimating displacement factors makes it possible to assess the suitability, in terms of greenhouse gases, of replacing non-wood materials or fuels with wood (Sathre and O'Connor 2010). As explained in Chapter 2:

$$DF = \frac{GHG_{\text{non-wood}} - GHG_{\text{wood}}}{Q_{\text{non-wood}} - Q_{\text{wood}}} \ (\text{tCO}_2\text{eq/m}^3)$$

where    $GHG = CO_2$ (in this case); Q = quantity used for the work.

The annual gain from displacement is thus valued at: DF × m³ used (tCO₂eq/year).

Displacement factors are generally expressed in tCO₂eq per m³ of wood used. Thus, a positive displacement factor (DF) represents a beneficial climate effect of wood use. However, DFs depend on many factors,

as explained in Chapter 2. Emissions from forestry and logging depend on the adopted practices that are evolving today.

For wood used as a material, we have used an average factor taken from the current literature to include the substitution effects, based on the volumes intended for this use and processing yields as indicated in section 4.2.6. In the literature, the factor ranges from 0.59 to 3.47 tCO$_2$eq per m$^3$ wood used and for France, the values used range from 1.1 (CNPF, 2017) to 1.6 (Roux et al., 2017), but the high values include the benefits of using processing waste in energy substitution. Like Valade et al. (2017), we deemed separating the material and energy effects to be a more thorough approach. We will therefore apply the value of 1.2 tCO$_2$eq per m$^3$ of timber after processing, and treat the benefit of using processing waste as wood energy separately. This means that, on average, building a wooden structure emits 1 GHG for every 2.2 GHG built with competing "conventional" materials. The choice to separate as so leads, in theory, to an energy substitution benefit that appears to be greater than that of the approaches that include processing waste in the factor.

For wood used as energy, the substitution effects greatly depend on practices (Chapter 2) and could even be negative (net emissions) using current practices or those predicted by some intensive scenarios. However, our scenario predicts that only wood that is not recoverable as sustainable products will be used for wood energy. With that in mind, and assuming an improvement in the efficiency of heating equipment, we will estimate a potential benefit from energy displacement. According to Oliver et al. (2014), the wood-energy displacement factor (DF) ranges from 0.37 to 0.64 tCO$_2$eq per m$^3$. However, these values do not include all emissions nor the carbon debt payback time (see Chapter 2), which is high in the event of clear-cutting (deadlock). Thus, for this study, an average factor of 0.4 tCO$_2$eq per m$^3$ is used.

Using displacement factors for mitigation scenarios deserves much more detailed analysis, so these estimated effects will just serve as an indication, with all the ensuing reservations linked to their wide range of possible values depending on the sector and societal variables.

## 4.2.8. Conversion factors

The objective is to quantify the scenarios studied in terms of the equivalent CO$_2$ stored. For wood (LB, DW, WP), the infradensity (dried tonnes per m$^3$ of green wood), carbon mass proportion (t-C/t-wood) and a C/CO$_2$ ratio of 3.664 must be used. We will use the conversion factors given by Lousteau (2010) and FCBA (2018), which incorporate these three parameters:

> For hardwoods:   1m$^3$ wood = 0.27 tonnes of carbon = 0.989 tCO$_2$eq
> For softwoods:    1m$^3$ wood = 0.22 tonnes of carbon = 0.806 tCO$_2$eq

The average conversion factor is then obtained by weighting these two values according to the respective volumes of softwood and hardwood. For French forests in 2019, we obtain a value of **0.930 tCO$_2$/m$^3$**.

## 4.2.9. Summary of the selected parameters

The parameters are summarised on the following page according to management situation. The "France" column gives the values used for the simulations at the national level, where P is reduced by 2% to reflect the 2% surface area covered by "uncountable" stands.

For the areas classified by IFN as "unidentified (UI)" (0.273 Mha) we have used the average values of the other species. For the areas classified as "uncountable (UC)" (0.280 Mha) we have taken average values from plantations aged 15 years old (D.10cm, Hm7m).

As explained in section 4.2.7, the average factor used for **displacement** is, with all the reservations mentioned, 1.2 tCO$_2$eq/m$^3$ for wood used as material and 0.4 tCO$_2$eq/m$^3$ for wood energy.

| Parameter | PeOak | SOak | CH | PuOak | HOak | BEE | ASH | HOR | OH | MP | SP | BP | DOU | SPR | SF | OS | UI | UC | France |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Parameters common to all situations and scenarios*** | | | | | | | | | | | | | | | | | | | |
| Gross stemwood production (P in m³/ha/year) | 4.76 | 5.28 | 6.62 | 2.20 | 1.34 | 5.64 | 5.85 | 5.09 | 4.53 | 7.39 | 4.43 | 5.04 | 14.62 | 12.86 | 11.74 | 5.00 | 5.00 | 5.00 | 5.61 |
| Initial volume of stemwood ($V_o$ in m³/ha) | 172 | 207 | 173 | 83 | 53 | 224 | 169 | 167 | 97 | 131 | 155 | 144 | 305 | 341 | 357 | 147 | 150 | 30 | 170 |
| Initial dead wood volume (ADW in m³/ha) | 23.6 | 19.0 | 46.9 | 11.1 | 6.5 | 29.1 | 30.7 | 28.6 | 26.7 | 20.0 | 23.6 | 18.5 | 32.2 | 41.8 | 49.0 | 26.8 | 22.0 | 7.1 | 22.9 |
| Expansion coefficients (Ec) | branches = 0.61; roots = 0.45 (total 1.06) | | | | | | | | | | | | branches = 0.33; roots = 0.40 (total 0.73) | | | 0.50 / 0.40 | | | 0.52 / 0.43 |
| ***Parameters for natural forests only (NF-M1, NF-M2)*** | | | | | | | | | | | | | | | | | | | |
| Initial mortality ($M_o$ in %LB): IFN 2013–2017 x 2 | 0.40 | 0.20 | 2.60 | 0.40 | 0.40 | 0.20 | 0.60 | 0.20 | 0.60 | 0.40 | 1.00 | 0.60 | 0.60 | 1.00 | 0.40 | 0.60 | 0.40 | 0.40 | 0.60 |
| Decomposition time of ADW (years) | 42 | | | 40 | | | 30 | | | 14 | | 16 | | 12 | | 13 | | 25 | 30 |
| ***Parameters for managed forests only (continuous cover forestry and deadlocks)*** | | | | | | | | | | | | | | | | | | | |
| Decomposition time of DW (years) | 34 | | | 33 | | | 25 | | | 12 | | 14 | | 10 | | 10 | | 11 | 22.9 |
| Proportion of timber from stem (% SW) | 63 | 66 | 32 | 24 | 13 | 60 | 48 | 23 | 36 | 65 | 59 | 60 | 75 | 70 | 78 | 63 | | 30 | 56% |
| Processing yield (%) | TIM = 40%; Wood for panels (Wp) and for posts/stakes (Wps) = 90% | | | | | | | | | TIM = 45%; Wp and Wps = 90% | | | | | | | | | 42% / 90% |
| ***Parameters for continuous cover forestry (CCF) only*** | | | | | | | | | | | | | | | | | | | |
| Initial mortality ($M_o$ in %LB): IFN 2013–2017 x 1.5 | 0.30 | 0.15 | 1.95 | 0.30 | 0.30 | 0.15 | 0.45 | 0.15 | 0.45 | 0.30 | 0.75 | 0.45 | 0.45 | 0.75 | 0.30 | 0.45 | 0.30 | 0.30 | 0.45 |
| Equilibrium volume of stemwood ($V_o$ in m³/ha) | 188 | 203 | 170 | 117 | 86 | 230 | 202 | 196 | 171 | 240 | 221 | 232 | 406 | 321 | 354 | 250 | 173 | 247 | 170 |
| HSW 2020 (%NP) according to IFN for French forests | 50% | 49% | 68% | 26% | 33% | 54% | 42% | 50% | 33% | 90% | 55% | 55% | 55% | 78% | 55% | 69% | 56% | 56% | 56% |
| HSW 2050 (%NP) for CCF in R60-M1 scenario | 120% | 100% | 120% | 50% | 40% | 110% | 100% | 80% | 40% | 50% | 55% | 55% | 70% | 120% | 110% | 40% | 60% | 40% | 84% |
| Branch harvesting (Hbr) | 50% to be adjusted according to species, transport and exploitability (H-mortality = 0) | | | | | | | | | | | | | | | | | | 50% |
| Mortality harvesting ($H_M$ stem + branches) | 20% (safety briefing, transport required for works) | | | | | | | | | | | | | | | | | | 20% |
| ***Parameters for deadlocks only (harvesting of 100% V + P (SW) for 2020–2050)*** | | | | | | | | | | | | | | | | | | | |
| Initial mortality ($M_o$ in %LB): IFN 2013–2017 x 4 | 0.80 | 0.40 | 5.20 | 0.80 | 0.80 | 0.40 | 1.20 | 0.40 | 1.20 | 0.80 | 2.00 | 1.20 | 1.20 | 2.00 | 0.80 | 1.20 | 0.80 | 0.80 | 1.20 |
| Branch harvesting (Hbr) | 75% (need to prepare the land before planting). | | | | | | | | | | | | | | | | | | |
| Mortality harvesting ($H_M$ stem + branches) | 75% (need to prepare the land before planting). | | | | | | | | | | | | | | | | | | |

*Main species: PeOak = pedunculate oak; SOak = sessile oak; PuOak = pubescent oak; HOak = holm oak; CH = chestnut; MP = maritime pine; SP = Scots pine; BP= black pine; DOU = Douglas fir; SPR = spruce; SF = silver fir; BEE = beech; ASH = ash; HOR = hornbeam; OS = other softwoods; OH = other hardwoods (including black locust). LB = total living biomass; SW = stemwood (main stem D>7cm); DW = natural dead wood (M); Harvesting: HSW = % of the net production of stemwood harvested.*

# 5. RESULTS AND DISCUSSION

## 5.1. Evolution of the harvesting rate of stemwood

We recall that the scenarios studied are characterised by:

| Management/mortality scenario | | Harvesting rate for continuous cover forestry (%) | | | Situations (% of forest managed) | |
|---|---|---|---|---|---|---|
| | | Stemwood (HSW) | Branches | Mortality | DEA 2020–2050 | CCF |
| Ecosystem prioritised | Ecos-M1 | Suitable for a linear decrease in the total harvest | 20%* | 10%* | 4.5 to 5.0% | 100 minus %deadlock |
| | Ecos-M2 | | | | 4.5 to 9.0% | |
| Compromise | R60-M1 | Suitable for a stable total harvest of 60 Mm³/year | 50%* | 20%* | 4.5 to 5.0% | |
| | R60-M2 | | | | 4.5 to 9.0% | |
| Sector prioritised | R95-M1 | Suitable for a linear increase in the total harvest up to 95 Mm³/year in 2050 | 75% | 75% | 4.5 to 5.0% | |
| | R95-M2 | | | | 4.5 to 9.0% | |

*75% in deadlocks.*

For all results, we will use the following legend:

NF = natural forest; CCF = continuous cover forestry; DEA = deadlocked stands; NP = net organic production; SW = stemwood; M1 = Slowly increasing mortality; M2 = Rapidly increasing mortality

| | | | | | |
|---|---|---|---|---|---|
| **SC** | Soil carbon storage | | **LB** | Living biomass | |
| **BDW** | Below-ground dead wood | | **WP** | Wood product storage | |
| **ADW** | Above-ground dead wood | | **Mat** | Material displacement | |

The application of the above scenarios results in the changes set out below. In this graph, harvesting is expressed as a percentage of the net production of stemwood for continuous cover forestry and as a percentage of the volume of standing stemwood in deadlocks (volume reflecting the regenerated area).
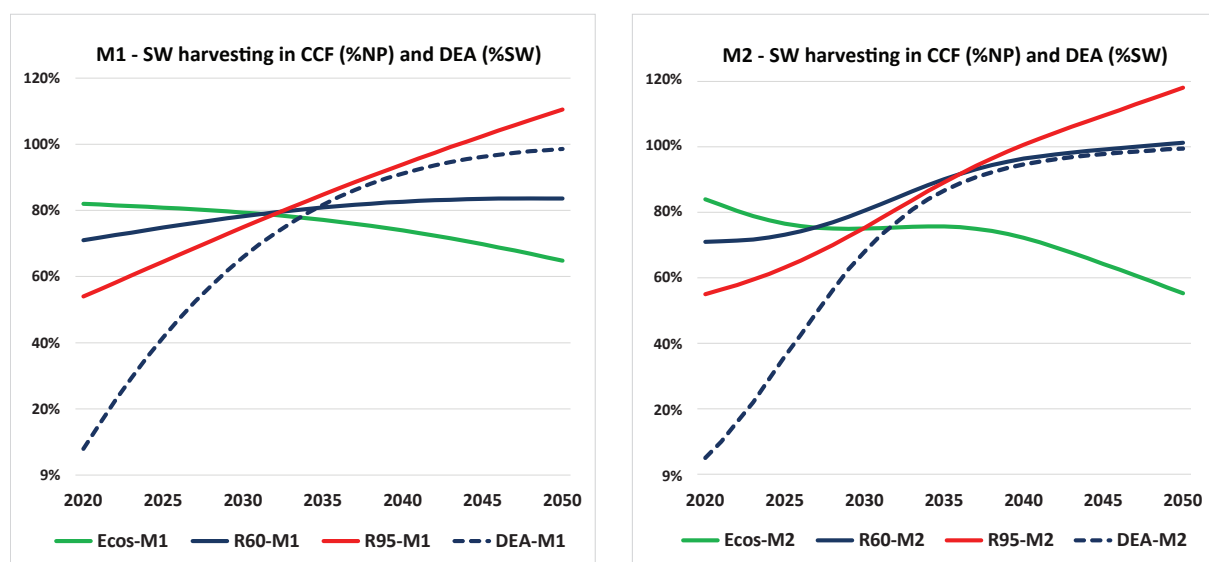
Following the reasoning set out in section 3.2, in these managed forests the current rate of harvesting of the net production of stemwood would be around 80%, including clear-cutting. However, compared with the current situation, branches and dead wood are subject to higher harvesting rates in the R95 scenario and lower rates in R60 and Ecos. This gives initial stemwood harvesting rates of between 57% (R95) and 82% (Ecos) in continuous cover forestry, with harvesting in deadlocked areas reducing all rates. It is clear that making the necessary changes regarding the type of harvesting would require a transition period. Based on the graphs, it can be assumed that this period would extend from 2020 until 2030.

In deadlocks, the rate increases rapidly initially, reaching 100% in 2050. From 2020 to 2030 it increases slightly less quickly in M2 than in M1 owing to the identification of new deadlock areas that are not immediately exploited (time is required for decision-making and administrative procedures). However, it then increases sharply because of the sudden rise in mortality rates. It should be noted that if we align the changes in the harvesting rates in these areas with the changes in mortality rates, we see a fairly rapid drop in the average standing volume, despite the contribution of new areas classified as deadlocks. In concrete terms, the change in the total standing volume in deadlocks will depend on the change in mortality rates, the adopted harvesting limits and the mortality thresholds above which managers facing total economic loss agree to operating losses. This forecast is therefore particularly complicated, and these difficulties must be taken into account when interpreting the results.
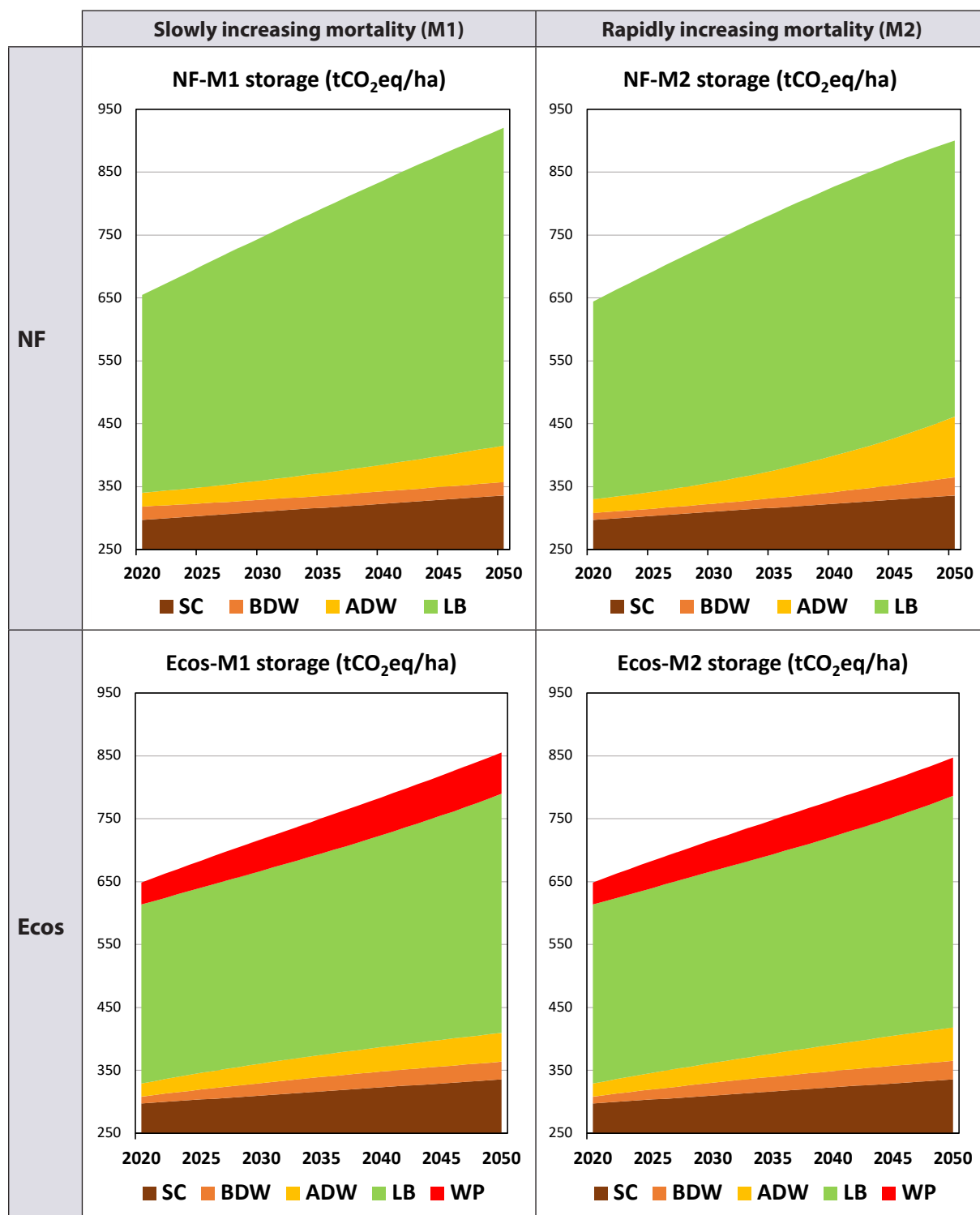
This change in harvesting does not define the distribution of the volumes harvested, but the scenario adopted assumes that stands comprising deadlock plots are harvested by clear-cutting of a maximum of 2 ha. In large homogeneous spruce plots, the trees' health and physical development could necessitate a succession of 2 ha clear-cuts, which would create the large openings that are already common, with consequences for the landscape, but also for ecology (soil, biodiversity).
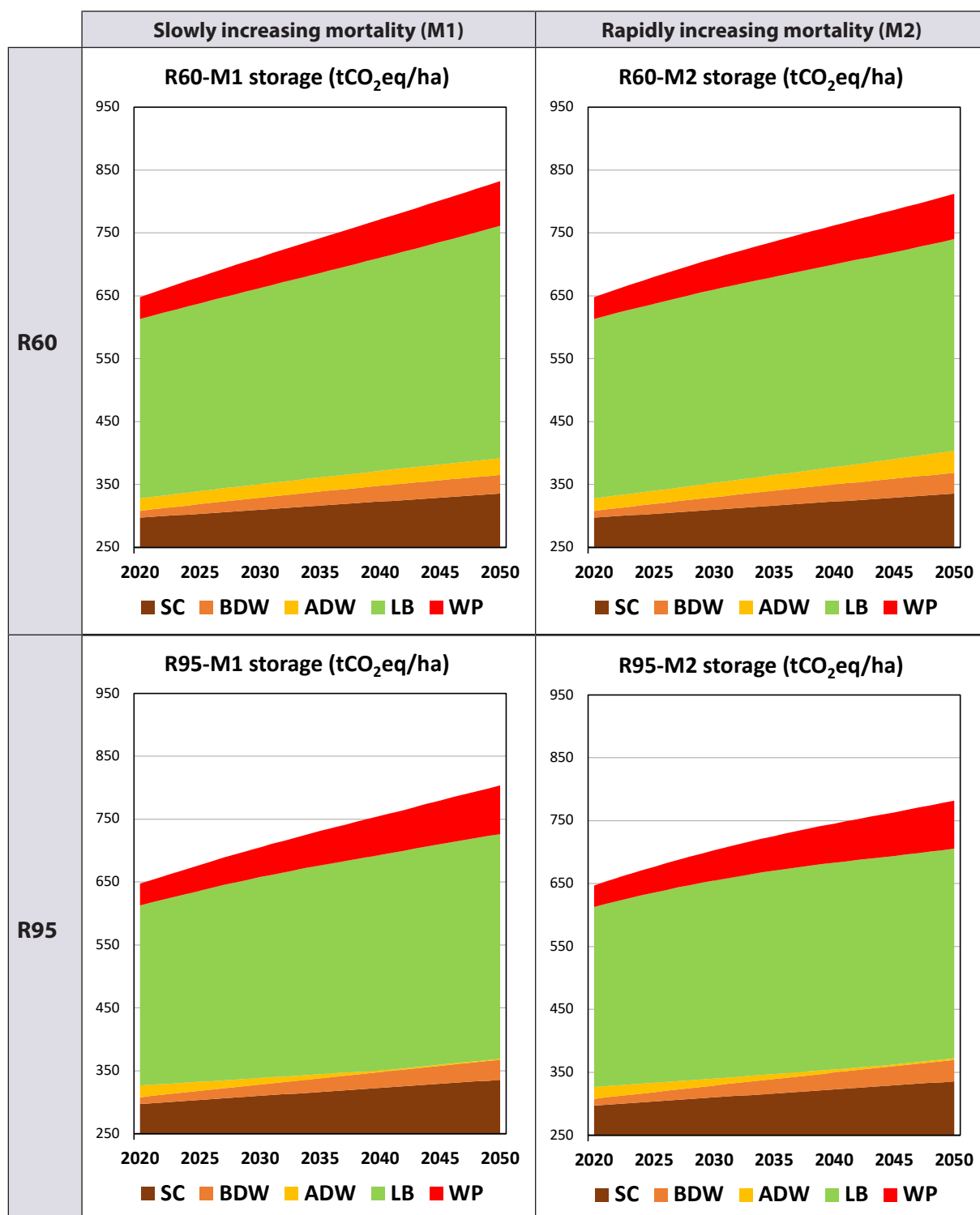
In the evolution of harvesting explained above, deadlocks contribute around 10 Mm$^3$/year during the first decade to "catch up" with current deadlocks, allowing for low initial stemwood harvesting in the R60 and R95 scenarios. It should then evolve quickly while the deadlocks are reforested and are therefore unproductive. The significant increase in the harvesting rate in the R95 scenario is the result of the planned increase in harvesting. For the Ecos scenario, the reduction in harvesting is caused by the objective of reaching an equilibrium volume in 2050 under the constraint of very low harvesting of branches and dead wood. The rate drops sharply when deadlocks are exploited. It should be recalled that this harvesting rate is an average resulting from the harvesting rates for each species, details of which are given in Chapter 4 for the R60 scenario. It should also be broken down across the entire surface area for each species by dividing it between forests according to their initial capital and the obstacles to extraction.

In any case, branch harvesting rates and "natural" mortality (which can be caused by management) are decisive factors, although they are not always visible in models that simulate changes in carbon stocks in the forest/wood system in France.

## 5.2. Changes in carbon stocks

Based on the management modality, the average stock will evolve as presented in the graphs below. The figures for Ecos, R60 and R95 combine all managed surfaces (continuous cover + deadlocked areas). This logic will be used for all following graphs.
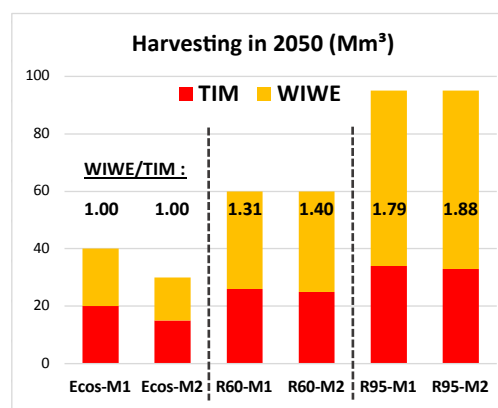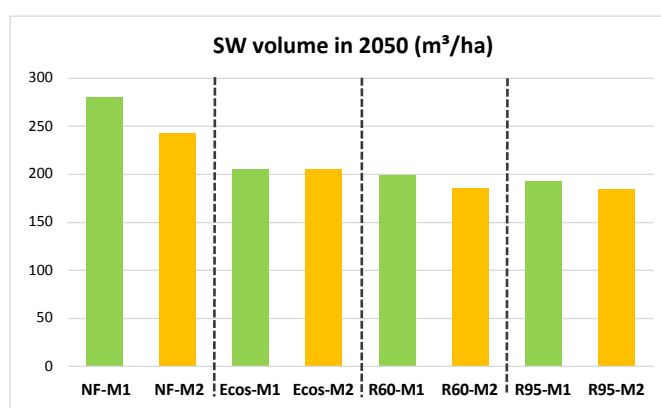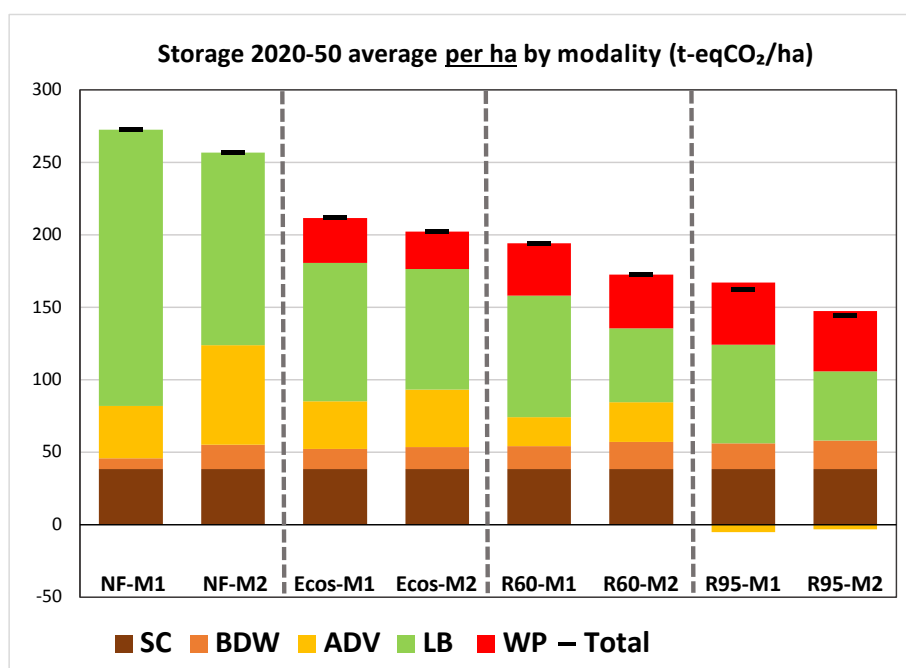
| | Slowly increasing mortality (M1) | Rapidly increasing mortality (M2) |
|---|---|---|

**R60**

### R60-M1 storage (tCO₂eq/ha)



### R60-M2 storage (tCO₂eq/ha)



**R95**

### R95-M1 storage (tCO₂eq/ha)



### R95-M2 storage (tCO₂eq/ha)



There are no "dips" in the change in total storage owing to the decapitalisation of reforested stands, as highlighted in Roux et al. (2017), because the areas concerned are limited and reforestation is spread over 30 years. However, the convex nature of this change is reduced, particularly in the Ecos scenario where it takes on an almost concave shape. Without the deadlocks, the curve in scenario R95 would be clearly convex.

The changes in the stocks of living biomass, dead biomass and wood products are a good reflection of the characteristics of the scenarios studied. The comparison between the effect of the scenarios is most visible in the stock variations calculated between 2020 and 2050 for all pools. This variation is shown below per hectare, with the levels of stemwood and harvesting reached in 2050.

Storage 2020-50 average per ha by modality (t-eqCO₂/ha)



SW volume in 2050 (m³/ha)



Harvesting in 2050 (Mm³)

*Note that in the storage change graph, the total change in R95 is the top of the bar (WP or MD) minus the loss of storage in dead wood (negative).*

The table below details the products harvested by scenario, assuming that the current supply chain pattern continues.

| Scenario | Total | Mm³ harvested | | | | Mm³ after processing | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | %TIM | WI-su | Papier | WE-harvested | TIM | WI-su | Waste | Paper | WE-Total |
| NF-M1 | 0 | 0% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NF-M2 | 0 | 0% | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ecos-M1 | 1,480 | 740 | 178 | 133 | 429 | 311 | 160 | 447 | 45 | 832 |
| Ecos-M2 | 1,350 | 674 | 162 | 122 | 392 | 284 | 146 | 408 | 41 | 758 |
| R60-M1 | 1,860 | 819 | 223 | 187 | 631 | 344 | 201 | 497 | 50 | 1,078 |
| R60-M2 | 1,860 | 775 | 223 | 195 | 667 | 326 | 201 | 472 | 47 | 1,091 |
| R95-M1 | 2,340 | 819 | 281 | 274 | 966 | 344 | 253 | 503 | 50 | 1,419 |
| R95-M2 | 2,340 | 812 | 281 | 275 | 972 | 341 | 253 | 500 | 50 | 1,421 |

*WI-su (sustainable) = wood for industry used in panels, posts, logs and poles.*

In addition, the table below summarises the harvesting and storage changes in the scenarios studied. The "change" columns give the 2020–2050 variations as percentages, and the SW-2050 CCF column gives the average volume of stemwood reached in 2050 in areas under continuous cover forestry. The last columns show the harvests in 2050.

| Scenario | CCF harvesting (%) | | 2020–2050 change in % | | | | SW-2050 (CCF) | Harvest 2050 in Mm³ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Branches | Mortality | LB | ADW | BDW | WP | | TIM | WIWE | Total | WIWE/TIM |
| NF-M1 | 0 | 0 | 65 | 169 | 68 | 0 | 280 | 0 | 0 | 0 | - |
| NF-M2 | | | 43 | 348 | 170 | 0 | 243 | 0 | 0 | 0 | - |
| Ecos-M1 | 20 | 10 | 33 | 173 | 151 | 98 | 205 | 20 | 20 | 40 | 1,00 |
| Ecos-M2 | | | 29 | 206 | 163 | 84 | 205 | 15 | 15 | 30 | 1,00 |
| R60-M1 | 50 | 20 | 30 | 103 | 168 | 113 | 199 | 26 | 34 | 60 | 1,31 |
| R60-M2 | | | 18 | 141 | 198 | 116 | 186 | 25 | 35 | 60 | 1,40 |
| R95-M1 | 75 | 75 | 25 | −24 | 187 | 133 | 193 | 34 | 61 | 95 | 1,79 |
| R95-M2 | | | 17 | −15 | 207 | 130 | 185 | 33 | 62 | 95 | 1,88 |

We can see that, starting from the same initial state, storage increases the most in natural forests, even in the event of increased mortality and despite the higher mortality rates linked to this approach (in terms of initial value and rate of evolution). The equilibrium volume is reached in the Ecos scenario, while it will be reached only around 2060 in the R60 scenario and also in the R95 scenario, where high harvesting of branches and dead wood makes it possible to save stemwood.

With or without harvesting, storage is lower where there is increased mortality (M2) – a modality that increases dead wood stocks in natural forests and where there is extensive (Ecos) and moderate (R60) management – but not in intensive harvesting (R95).

Naturally, the M2 scenario of increased mortality produces lower living stocks and more dead wood, with the exception of the Ecos scenario where management adapts to natural factors to optimise the forest environment by increasing the volume of stemwood.

We can therefore see that the storage effect in biomass is largely greater than storage in products. This pool becomes important in high-harvest scenarios (R95), where displacement also becomes significant. Thus, the carbon effect in these high-harvest scenarios is even more dependent on the way wood is harvested, transported and processed, and estimating their impact depends further still on the estimation of product lifetimes and displacement factors. These effects will be discussed in the following paragraph.

The difference in harvesting between Ecos, R60 and R95 owes largely to branch harvesting and mortality. The appropriateness of harvesting branches with small and medium diameters is questionable, given the related energy costs and the effects of this practice on soil and biodiversity. Once again, the simulated rates are averages that must be adjusted in accordance with the situation (hardwood or softwood, slope or plain, rural or peri-urban space, etc.)

The table also illustrates that mortality affects the sink in 2050 in several ways:

- through dead wood stocks (higher in M2), although the R95 scenario produces a net loss of dead wood stocks, including in M2;
- through wood product stocks and the proportion of timber in the harvest (M1 stores more and produces more timber);
- through the difference in the initial level of mortality and its rate of change, which are considered greater in natural forests. This methodological choice leads to a net loss of living biomass (LB) in M2, consistent with the marked increase in dead biomass stocks. The difference in mortality between NF and Ecos is likely, however, because "prudent" forest management can reduce mortality by reducing inter-individual competition. On the other hand, if we consider that mortalities in NF should be reduced, they must be increased symmetrically for R95 because intensive management can cause non-competitive mortalities (sudden exposure to light, root asphyxia, skidding damage, etc.). This parameter is therefore important and must be the subject of in-depth research, even if it is impossible to predict the changes in mortality with total accuracy.

In the Ecos and R60 scenarios, the ratios of wood harvested for industry or energy generation to timber are lower than the current actual values. Indeed, any decrease in the harvesting of branches and dead wood produces an increase in the proportion of timber in harvests. However, in current practices, the difference also stems from the use of some potential timber as wood harvested for industry or for energy generation. Increased mortality

also reduces the proportion of timber, so that for a given scenario, the ratio of wood harvested for industry or energy generation to timber is higher for M2 than for M1.

Finally, using the method described in section 4.2.7, below we provide an estimate of the potential gain in emissions avoided by **substituting wood for other carbon energies**. These avoided emissions represent between 10% (Ecos-M2) and 24% (R95-M2) of the total obtained for the other leveraging effects (biomass and wood used as material). Adding the potential gain from energy displacement does not result in a substantial difference between the scenarios in terms of storage in 2020–2050: the more extensive the scenario in terms of harvesting, the greater the total climate benefit.

### Assessing storage changes and gains made through substitution between 2020 and 2050

The total storage per hectare is shown below. Even with optimized wood products and with our hypotheses of higher mortality and lower production in natural forests, total storage (ecosystem + products) is by far more effective when forests are not exploited (natural forests). The increased mortality (M2) does not change this finding, while the R95 scenario is even less effective.
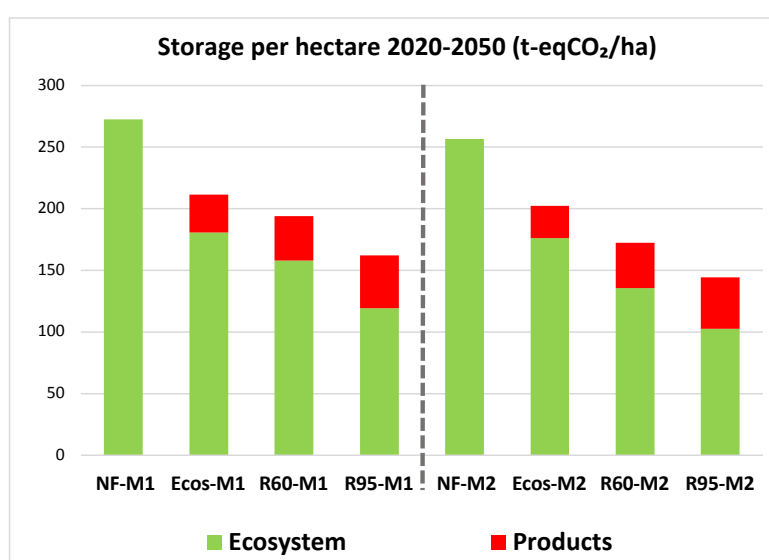


However, simulating the substitution effects tempers this result. The overall mitigation potential (France) by substitution and sequestration for the 2020–2050 period is presented by scenario below. It is clear that adding the potential substitution gains alone is not enough to make increased harvesting beneficial to the climate. However, under both climate scenarios and with all the caution taken in this report, the more extensive the scenario is in terms of harvesting, the higher the total climate benefit.
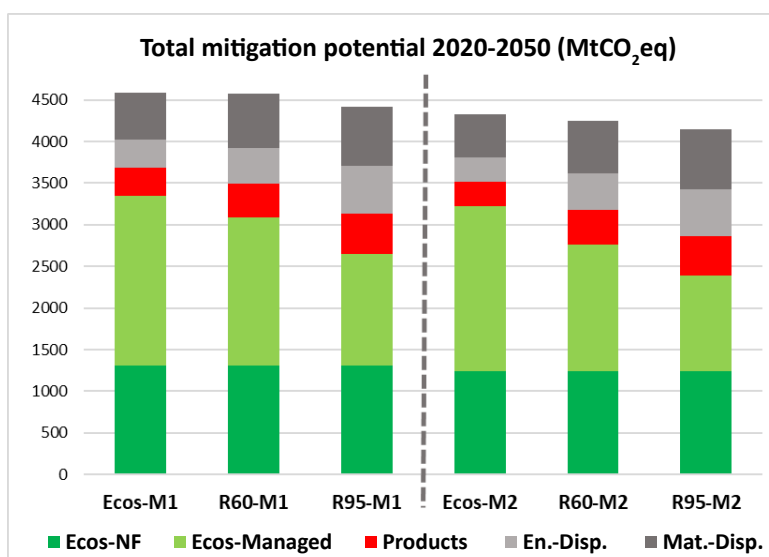
## 5.3. Quantity and quality of dead wood

The graph below shows the levels of dead wood in 2050 under the management scenario and in natural forests, compared to the levels estimated in 2020 (IFN, 2019).

**Deadwood in 2019 (France) and in 2050 according to scenario (m³/ha)**



*Average managed forests only*
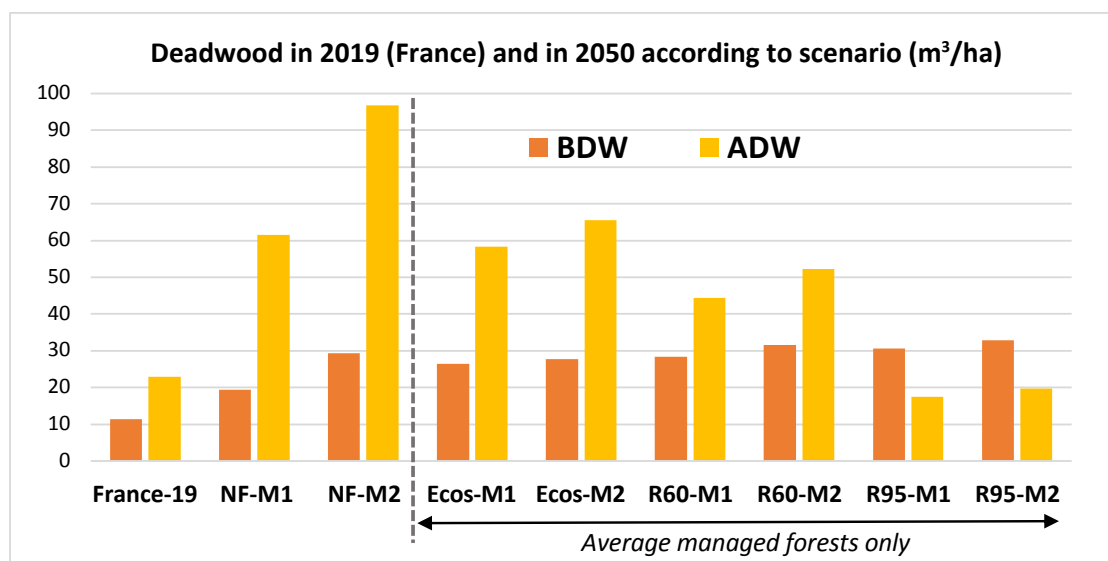
We can see that the volume of below-ground dead wood evolves in a similar way, even if it is lower in natural forests, with little change in mortality (M1). This is partly due to the assumption that 30% of stumps will die after cutting under continuous cover forestry – a rate that requires further analysis. On the other hand, the volume of above-ground dead wood reached in 2050 registers very disparate levels. In natural forests, the volume of above-ground dead wood reaches 63 m³/ha in M1 and 104 m³/ha in M2. In scenario R60-M1 it stands at 42 m³/ha, whereas in scenario R95-M1 it is reduced to 17 m"/ha in total. In natural forests, the increase is simply the result of mortality, while in continuous cover forestry it results from the low harvest of trees that have died naturally and the partial harvest of branches. In deadlocked stands, the decrease is explained by the harvest of 75% of above-ground volume and branches. It is in this third situation that the highest load of below-ground dead wood is found, owing to the cutting of all trees in the initial stand and the low survival rate of the stumps.

Not all types of dead wood are of equal benefit for biodiversity, but it is difficult to break down our results by dead wood quality. There is a greater presence of stemwood in natural forests, while branches are more common in continuous cover forestry, and stumps are very common in deadlocked stands. The Ecos scenario produces more large branches, and the R95 scenario results in smallwood that decomposes quickly and that is important for fertility, but provides little benefit for biodiversity. It would therefore be more accurate to vary the decomposition time according to the scenario, as this variation further reduces storage in the R95 scenario.

According to IFN (2019), in 2018 the average dead wood stock in France is around 22.9 m³/ha and would break down as follows:

| Dead wood type/Class D. | D < 17.5 cm | WP | DW | LD | VLD | France average |
|---|---|---|---|---|---|---|
| Standing + windfall | Not specified | 3.2 | 2.6 | 0.8 | 0.3 | 6.9 |
| On the ground | 9.9 | 2.9 | 1.3 | 1.2 | 0.7 | 16.0 |
| France average | 9.9 | 6.1 | 3.9 | 2.0 | 1.0 | 22.9 |

Dead wood on the ground and dead wood with a diameter under 30cm therefore makes up the majority.

However, the IFN classification is not well suited to analysing biodiversity because, ecologically speaking, the "windfallen" and "on the ground" categories become confused. Moreover, it is likely that in natural forests the volume ratio between standing and on-ground wood is higher than in managed forests, and therefore higher than the IFN data. Since there are no more suitable IFN statistics, this distribution is used to estimate the proportion of standing and windfallen dead wood in relation to dead wood on the ground. In scenario R60, this gives the following results for 2050:
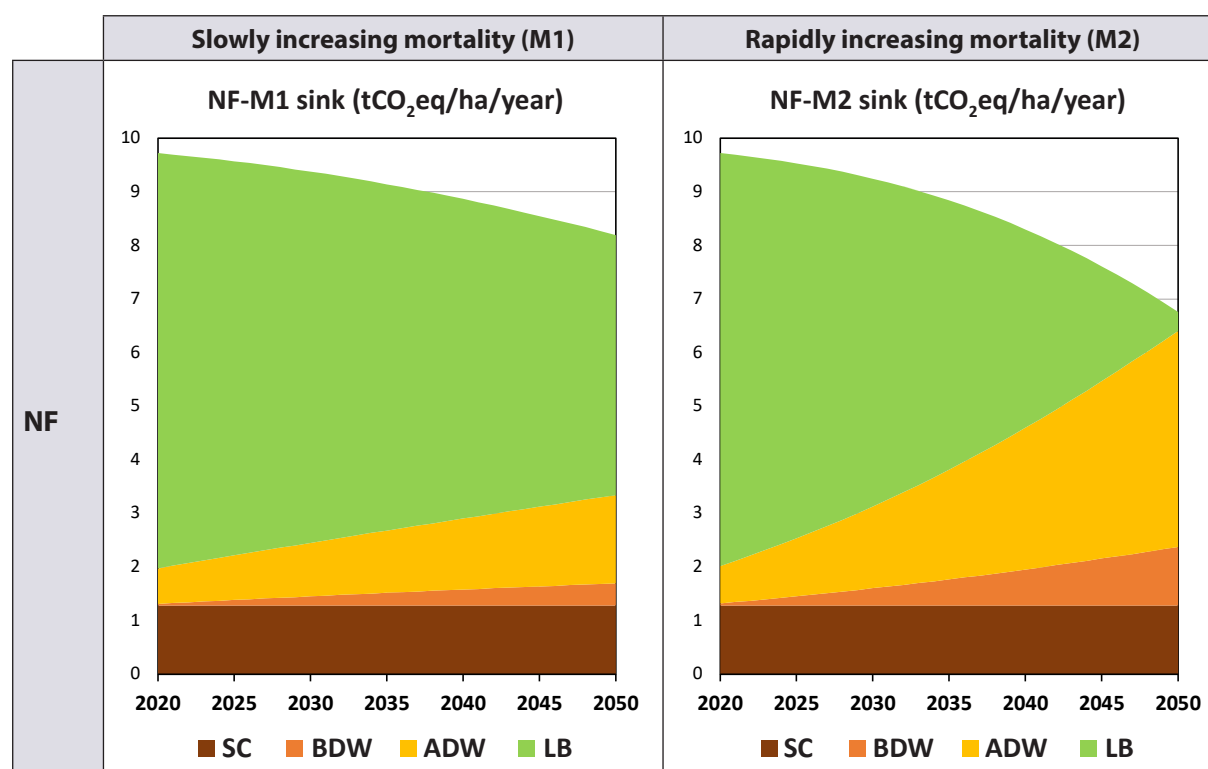
| *m³/ha* | | Above-ground dead wood | | | |
|---|---|---|---|---|---|
| | | standing+ windfall | on the ground | total | BDW |
| Natural forests | NF | 19 | 44 | 63 | 16 |
| Forests under continuous cover forestry | CCF | 13 | 30 | 42 | 26 |
| Deadlocked stands | DEA | 3 | 9 | 12 | 32 |
| **French forests** | **France** | **14** | **32** | **46** | **24** |

The distribution of dead wood by diameter cannot be determined, but the proportion of large- and very large-diameter wood will certainly be higher in natural forests than in managed forests.
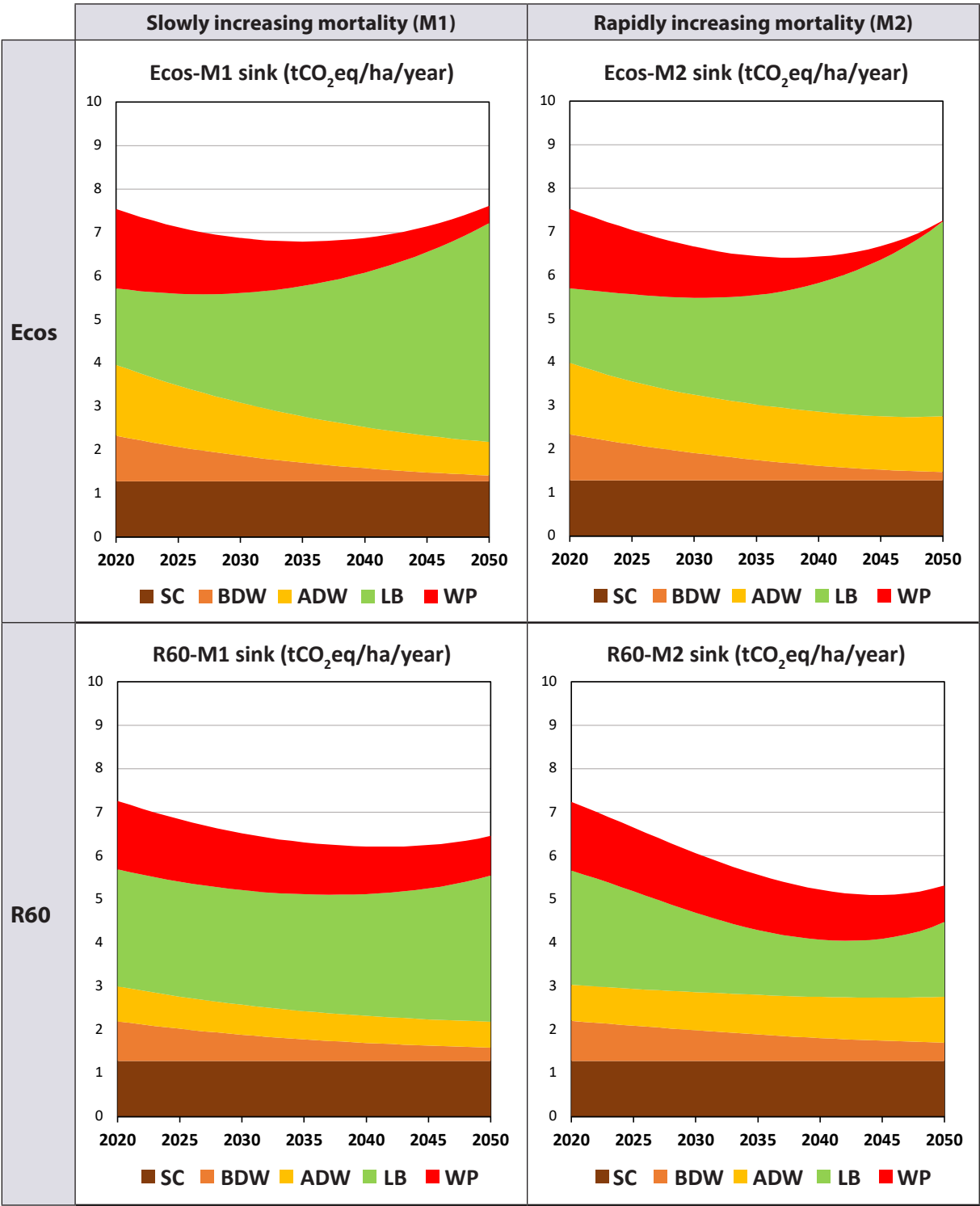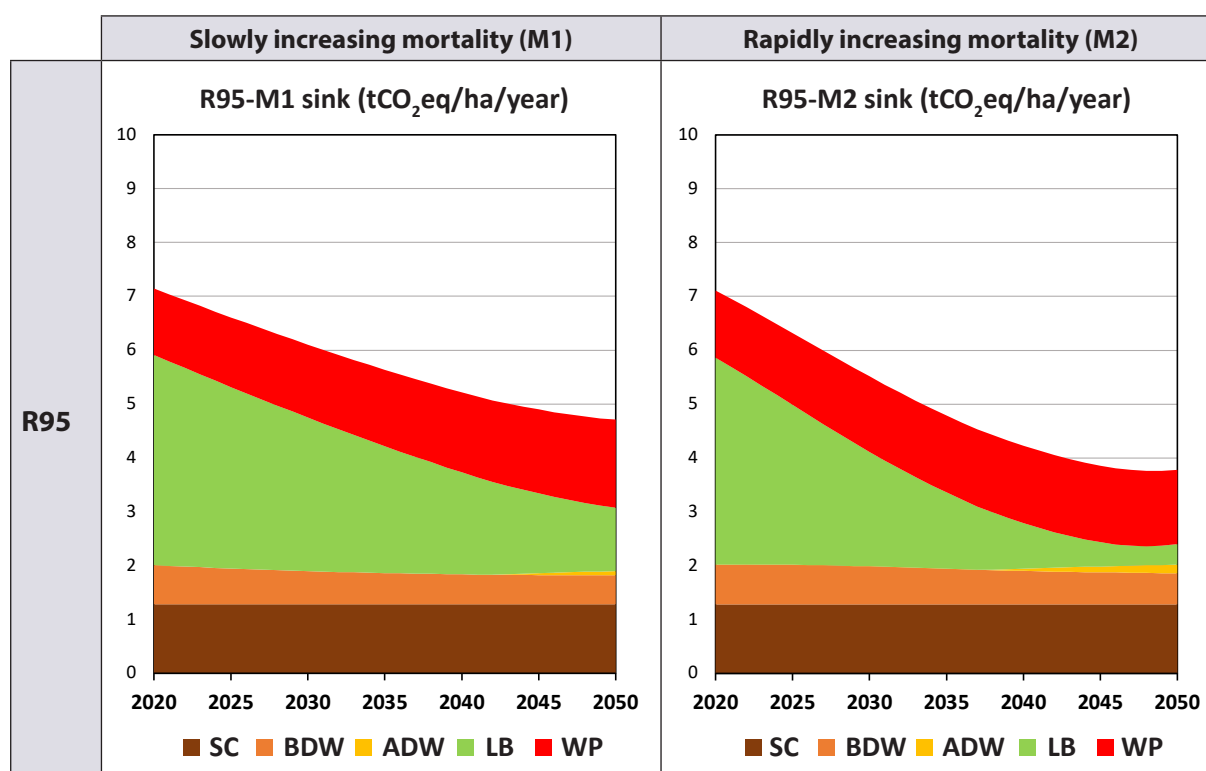
This carbon pool merits further research.

## 5.4. Evolution of the sink

The sink refers to the annual net carbon flows of the forest + products system, calculated as the difference in storage between two consecutive years. Mathematically, it is therefore derived from the function that describes the change in storage. For our different scenarios, we calculate the average change per hectare below:

| Slowly increasing mortality (M1) | Rapidly increasing mortality (M2) |
|---|---|
| **R95-M1 sink (tCO$_2$eq/ha/year)** | **R95-M2 sink (tCO$_2$eq/ha/year)** |

R95

SC   BDW   ADW   LB   WP

Excluding soil and products, the total initial sink for France is estimated at -84 MtCO$_2$eq/year, which is consistent with current estimates (EFESE, 2019).This figure is consistent with current estimates (EFESE, 2019). This value depends on the CO$_2$/m$^3$ ratio used (here 0.93) and is therefore not absolute. The initial difference in sinks between the Ecos, R60 and R95 scenarios owes to wood products, with the scenario being applied from 2020.

In natural forests in the M1 mortality scenario, between 2020 and 2050 the sink per hectare decreases slightly owing to the progressive decrease in net production (gross production – mortality). As mentioned, this scenario assumes that the areas retained as natural forests are mainly forests that have already been exploited, rather than young stands, so there is already active competition for resources. The decrease is more pronounced in the M2 mortality scenario, where the living biomass sink becomes almost nil in favour of dead wood. Therefore, the equilibrium between production and mortality (a living biomass ceiling) would be approached in 2050, while the total biomass would continue to evolve significantly thanks to the addition of dead wood. However, the relatively high increase used for the mortality rate in natural forests affects these results.

In managed forests, the more or less sustainable decline of the sink owes mainly to the exploitation of dead-locked stands, which also leads to a decrease in the below-ground dead wood sink through root decomposition.

In Ecos, the total sink increases due to the arrival of plantations whose production exceeds the losses caused by harvesting, decreasing between 2020 and 2050. This is the only approach where the total sink in the M2 scenario is greater than that of M1 because of the larger decrease in harvests in M2 between 2020 and 2050. In the increased mortality scenario (M2), management that adapts to natural changes while seeking to reduce mortality (Ecos) could thus lead in 2050 to an annual sink that is higher than that of natural forests (NF). However, this result should be viewed with caution, as it assumes a mortality rate that evolves more sharply in natural forests than in managed forests as described in Chapter 3.

In scenario R60, the sink appears relatively stable, with the prospect of a slight increase thanks to planting carried out after deadlocked stands have been exploited. In the M2 mortality scenario, however, this increase does not manage to compensate for the decline in the sink seen from 2020 to 2040.

In the R95 scenario, the sink decreases continuously. In 2050 the living biomass sink is small but not zero, and the sink generated by the supply of wood products is significant, but the negative dead wood sink reduces

the total flow. The wood products sink in the M2 scenario is lower than in M1 owing to the lower proportion of timber.

In summary, in terms of the annual flow between 2020 and 2050, the Ecos scenario seems the most efficient, the R95 scenario leads to significant erosion and the R60 scenario maintains the current sink. In 2050, France's total sink excluding soil and products is expected to be 31 MtCO$_2$eq/year lower, which is in line with the estimate given by the National Energy and Climate Plan.

It should be noted that owing to a lack of references, we have chosen not to vary the rate of soil carbon storage, although differences could appear between scenarios for this pool. This would probably be to the detriment of the intensive scenario because of increased exposure of the soil surface and the harvesting of branches and dead wood, some of which feeds the soil storage in the other scenarios.

Lastly, the mortality rate used for post-cutting stumps (50% for CCF and 80% for deadlocks) remains poorly documented. If it is underestimated, the differences between scenarios tend to widen, with lower storage rates in scenarios with significant harvesting, particularly R95.

Lastly, it should be noted that these comparisons do not highlight the potential differences between clear-cutting harvesting and thinning harvesting. The objective was to study the variations in harvesting rates in an overall management scenario. However, according to the literature (Chapter 2), this difference in the processing of stands could have a significant impact on soil carbon storage, at least in the first metre, where the average of 300 tCO$_2$eq/ha represents almost 50% of the total storage analysed here. Integrating these effects would probably make the R95 scenario (even) less attractive in terms of climate change mitigation.

## 5.5. Detailed analysis of the R60-M1 scenario (compromise)

### 5.5.1. Evolution of storage by management situation

Changes in carbon storage per hectare by pool varies greatly between situations, as shown in the graphs below.
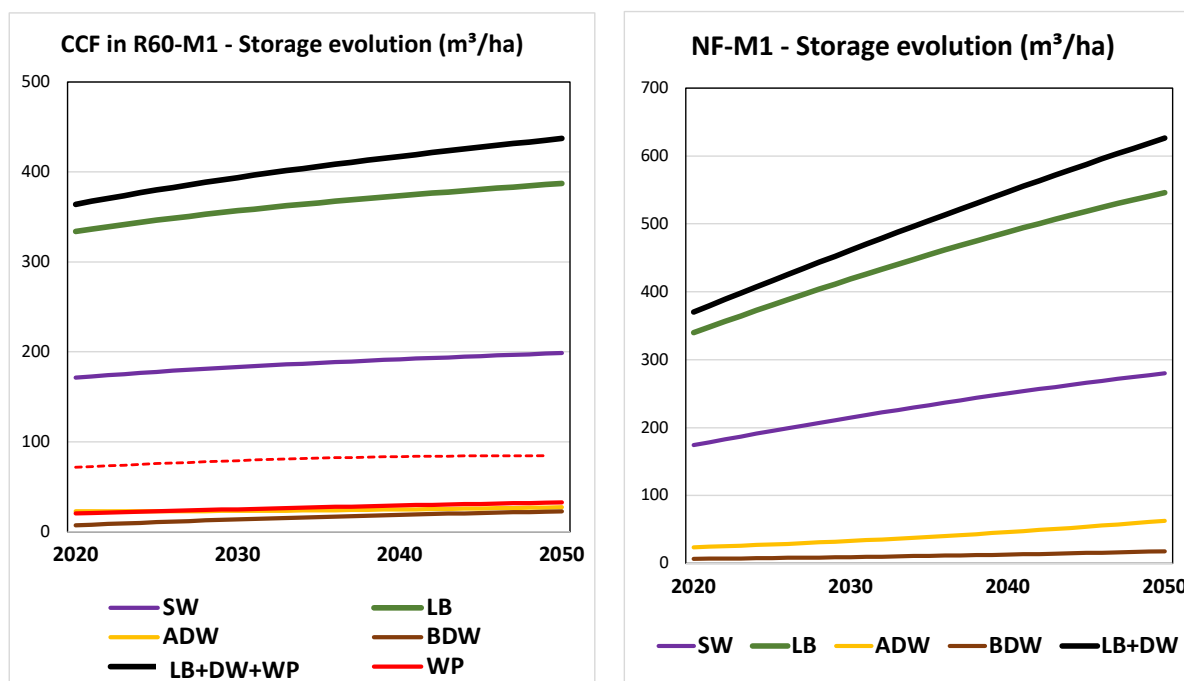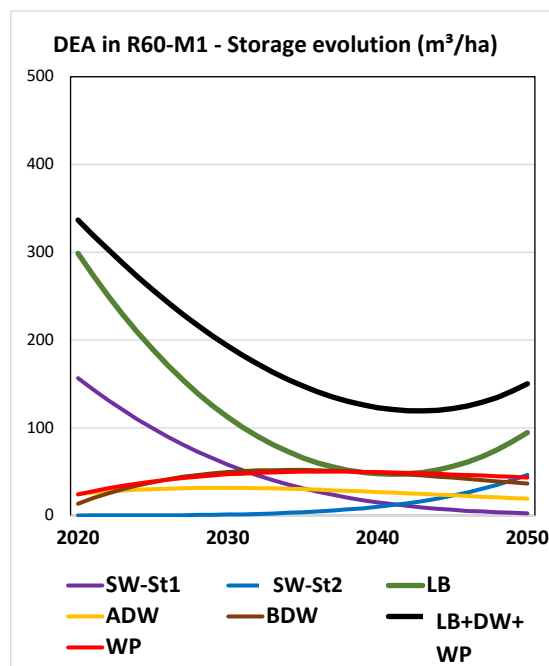


*SW = stemwood, LB = total living biomass, ADW = above-ground dead wood (m³/ha);*
*WP = wood products (m³-eq/ha equivalents); HSW = harvest rate of net annual production of stemwood (%).*

In natural forests, storage increases sharply, including in dead wood. In continuous cover forestry, storage evolves slowly and steadily. The storage provided by dead wood increases slightly. Storage in wood products grows a little faster, but its curve is almost identical to that of dead wood when compared with the largely dominant storage of living biomass.

In deadlocks, living biomass falls until 2040 (initial stands are exploited at a rate of 90%, young plantations are not yet productive), then rises thanks to the stocks created by the new plantations. The storage provided by wood products first increases, then decreases slightly because its contribution to storage – which is low after 2040 – can no longer compensate for end-of-life losses. The storage from below-ground dead wood follows a similar curve for the same reason. The storage provided by above-ground dead wood is initially stable and then decreases slightly owing to the decomposition of branches left on the ground (25%) after the initial stands have been exploited.
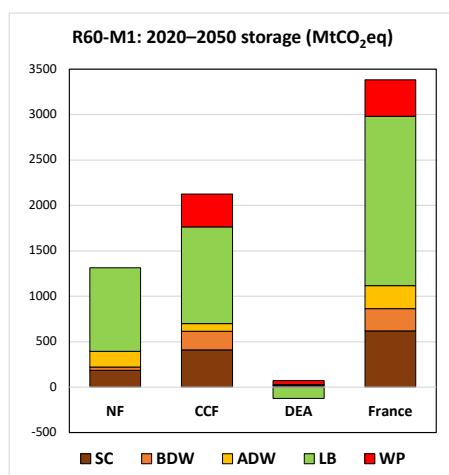
In total for France (graph below left), total storage in the ecosystem between 2020 and 2050 would be 49% in natural forests and 51% in areas under continuous cover forestry, a sink that would compensate for the net loss seen in deadlocks. Over this period, on the other hand, deadlocks generate 15% of the wood harvested, which



*St1 = initial stand (deadlock)*
*St2 = plantation with exploitation of St1.*

is 19 times more per hectare than other managed areas (the capital is harvested, rather than the increase). Volumes/ha (graph on the right) increase significantly in natural forests, moderately in areas under continuous cover forestry and fall in deadlocks (net balance between the initial exploited stand and the replacement plantation).

For the 16 Mha of French forest, combining the figures from the three situations **brings total storage over the 2020–2050 period to 3.38 Gt-CO$_2$eq:** 55% in living biomass, 15% in necromass, 18% in soil carbon, and 12% in wood products.
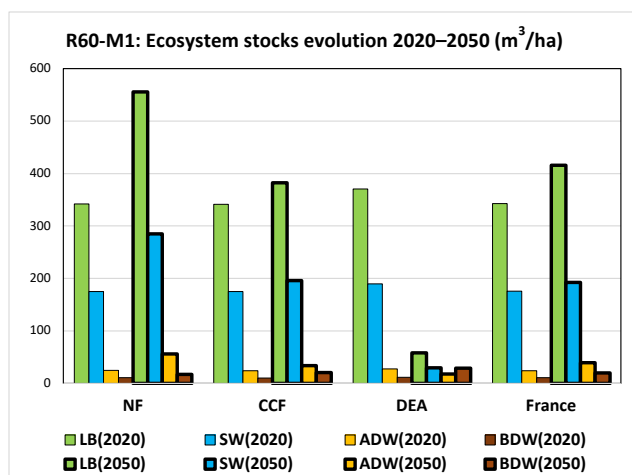




*NF = Natural forest*
*CCF = Continuous cover forestry*
*DEA = Deadlocks*
*France = NF + CCF + DEA*

*SC = soil carbon storage*
*LB = Living biomass*
*ADW/BDW= Above-ground dead wood (a)/below-ground dead wood (b)*
*WP = Sustainable wood products stocks*
*MD = material displacement*

Changes in the standing volumes per hectare vary greatly depending on the species and in accordance with the chosen harvesting rates. In the graph below, carbon storage increases only slightly for low-yield species or species facing health issues (holm oak, Scots pine, chestnut and ash), increases sharply for some species (maritime pine, miscellaneous softwoods and hardwoods) and exceeds 400m³/ha for Douglas fir. However, it is possible that the mortality rate may increase faster than expected in this calculation for spruce, and perhaps also for pedunculate oak and silver fir. For Douglas fir, competition could lead to an increase in the mortality rate as a percentage of standing volume. The simulation could therefore be refined by varying the mortality evolution factor according to species. But in any case, this calculation indicates that French forests are not currently "over-capitalised and ageing".



**R60-M1 : Evolution of stemwood volume per hectare (m³/ha)**
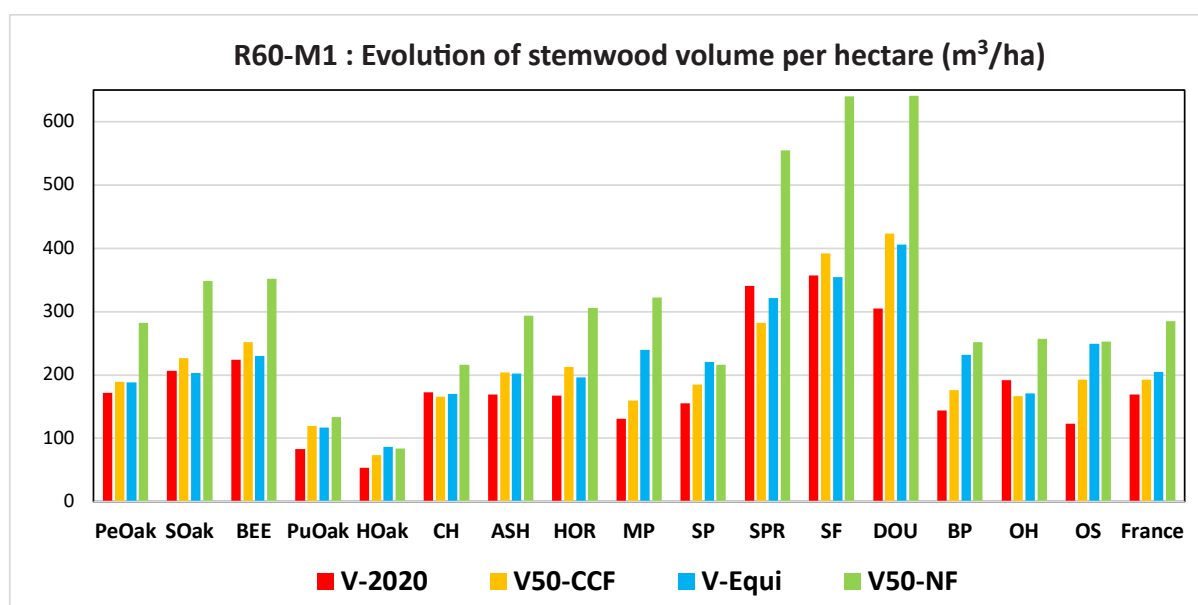
*Evolution of stemwood volumes per hectare for each species in natural forests (V50-NF) and under continuous cover forestry (V50-CCF), compared to the initial volume (V-2020) and the stock in equilibrium under continuous cover forestry (V-Equi).*

*Species codes: PeOak = pedunculate oak; SOak = sessile oak; BEE = beech; PuOak = pubescent oak; HO = holm oak; CH = chestnut; ASH = ash; HOR = hornbeam; MP = maritime pine; SP = Scots pine; BP = black pine; SPR = spruce; SF = silver fir; DOU = Douglas fir; OS = other softwoods; OH = other hardwoods (including black locust).*

In areas under continuous cover forestry, in 2050 the average volume of stemwood would be **199 m³/ha:** an 18% increase on the 2018 national average. Achieving the estimated equilibrium level (205 m³/ha) would require a reduction in the harvesting of stemwood to give a total harvest of 55 Mm³/year in 2050, or an increase in the harvest levels of branches and dead trees.

For Douglas fir, spruce and fir, the volumes in natural forests are high in terms of initial capital and high yield. However, given recent changes (2018–2019), this volume seems unlikely for spruce, consistent with an under-estimated mortality rate (IFN, 2019 and change 2020–2050). The same may be true to a lesser extent for silver fir, and even perhaps for beech and pedunculate oak. This highlights the usefulness of a finer estimate of mortality in 2020 and beyond, by species – an estimate that nevertheless seems very difficult to make with current data.

With regard to each species' equilibrium level, some positive or negative differences remain for some species, owing to the difficulty of closing the initial gap within 30 years, despite the substantial changes in harvesting rates (table in section 4.2.9). The volume/ha decreases for chestnut and spruce owing to their health crisis. It remains far from stock in equilibrium for ash (health crisis), Scots pine and black pine (fairly high IFN mortality rate), maritime pine (high initial undercapitalisation) and miscellaneous softwoods (mostly young). It exceeds the equilibrium for silver fir and sessile oak (initial over-capitalisation) and slightly exceeds it for beech (difficulties in extraction). However, distributing harvesting among species as presented here is just one of several options when applying the R60-M1 scenario.

We must be mindful that in continuous cover forestry, basal area and equilibrium volume/ha remain values around which we seek to oscillate (Pro Silva France, 2014), with time-related differences of around 20% to 30%, even once the equilibrium has been reached. We also recall that this estimated equilibrium volume is related to the selected harvesting limits and the optimal basal areas estimated for each species. It can therefore be reassessed by observing foresters and researchers, such as the Uneven-Aged Forest Association (AFI) network (Susse et al., 2009).

## 5.5.2. Spatial distribution of harvesting

An overall management and harvesting strategy does not determine how these harvests are distributed in space. Moreover, the constant harvesting of 60 Mm³/year may mask significant differences between regions and forests owing to the initial situation, productivity and extraction conditions. Today, there are significant such gaps between "abandoned" (and manageable) forests and (over-)exploited forests. In our calculations, the initial harvesting rate does not exceed the estimated current harvesting percentage, but in 2020 it results from a broad range of practices, including un-thinned plots, on the one hand, and relatively early destocking via clear-cutting, on the other.

Additionally, maintaining a constant total harvest of 60 Mm³/year could be achieved through a higher harvest of branches and dead wood than proposed in this "compromise" scenario, which would lead to higher levels of stemwood and lower levels of dead wood in 2050.

It is difficult to estimate the current level of branch and dead wood harvesting:

– For branches, it can be roughly estimated from the current branch harvest, estimated at 15 Mm³/year (Total harvest — SW harvest), out of a total production by the area currently managed (section 2.2.1) of around 80 Mm³/year, and 27 Mm³/year for branches. These figures suggest branches are harvested at a rate of around 55% in 2019, which seems plausible. The Ecos scenario therefore constitutes a sharp decrease in this rate, the R60 scenario a slight decrease and the R95 scenario a sharp increase.

– No harvesting figures are available for dead wood, so it is difficult to compare our scenarios against the current situation. However, it is likely that in managed forests, the current rate is around 50%, so R95 would result in an increase and the other two scenarios, a sharp decrease. There is no doubt that maintaining a harvesting rate of 75% for dead wood in all managed forests would lead, in those forests, to at least a three-fold reduction in dead wood storage per hectare, with significant consequences for biodiversity.

Reducing the harvesting of dead branches and dead trees will therefore require better spatial and temporal distribution of harvesting – a chief characteristic of continuous cover forestry – to enable harvesting of 60 Mm³ in 2020. However, applying such scenarios would certainly require a transition period and clear political will.

These simulations are undertaken as part of a forestry system that avoids clear-cutting apart from in stands considered to be deadlocks, which by definition distributes harvesting more evenly in space and time than even-aged high forests or a simple coppice system. Thus, moderate variations in the spatial distribution of harvesting (by region and stand type) should not affect the results significantly. The proposed scenario is designed to avoid differences in harvesting rates between intensively managed forests (e.g. state-owned forests and large private estates) and "abandoned" forests (small private forests, which are often suddenly over-harvested). To establish a truly realistic national scenario that takes into account regional disparities, a strategy should therefore be built at the most local level possible, depending on data availability and relia-bility. The more detailed the analysis in terms of the regions, the more the parameters will have to be adjusted and the greater the number of possible scenarios, hence the need for decentralised and collective work. This more targeted approach would allow the equilibrium volume/ha and the harvesting limit for each species in a given context to be defined more precisely. It would enable the national strategy (a top-down approach) to be compared with regional strategies (a bottom-up approach), in order to harmonise the two approaches.

### 5.5.3. Harvesting and stocks of generated products

Estimated volumes of various products were given in section 5.2. The following graphs show the breakdown of volumes of timber and wood harvested for industry or for energy generation by species. It is important to remember that these breakdowns may vary depending on the different harvesting targets selected and applied to different species.
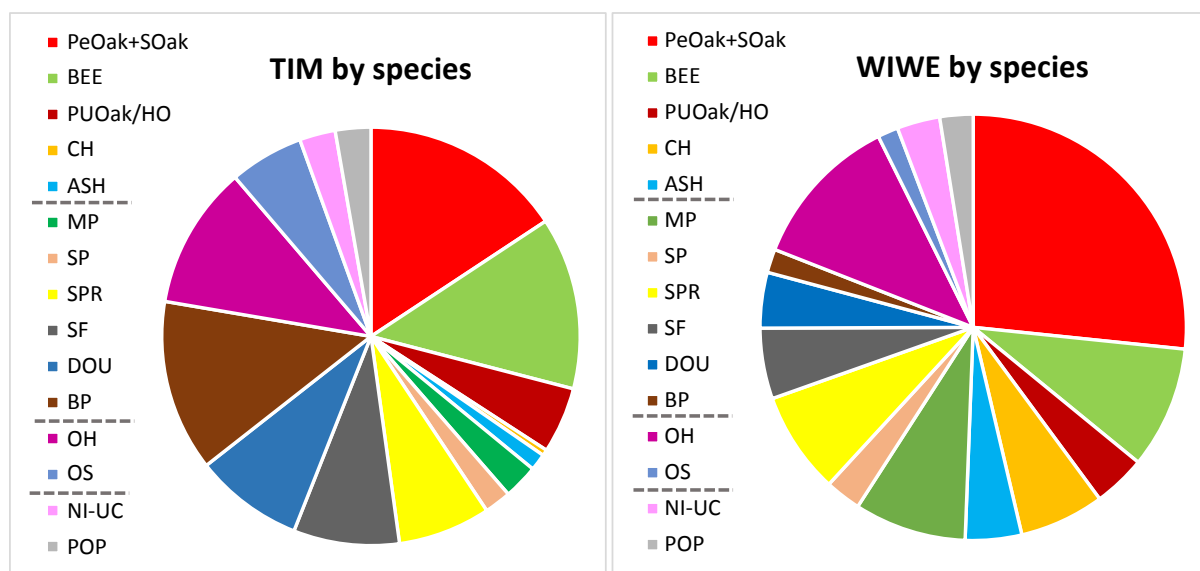


*Species key: PeOak = pedunculate oak; SOak = sessile oak; BEE = beech; PuOak = pubescent oak; HO = holm oak; CH = chestnut; ASH = ash; MP = maritime pine; SP = Scots pine; BP = black pine; SPR = spruce; SF = silver fir; DOU = Douglas fir; OH = other hardwoods (including hornbeam and black locust) ; OS = other softwoods.*

The total harvest is made up of 43.3% timber and 56.7% wood harvested for industry or for energy generation, in a **WIWE/TIM ratio of 1.31**. This is a low value compared with traditional ratios of between 1.65 (MTES, 2018a) and 2.10 (FCBA, 2019), which assume that a quarter of potential timber according to the IFN is used in industry and energy generation. Compared with the current reality, our scenario foresees recovering significantly more hardwood timber potential. This difference also owes to the decision to harvest few branches and not to harvest natural dead wood. In any case, a significant effort must be made to avoid wasting the potential of hardwood.

By comparison, the R95-M1 scenario gives a WIWE/TIM ratio of 1.79, even using our assumed optimal recovery of potential timber, which indicates an increase in wood energy, and therefore fewer products storing more carbon in a sustainable way. In any case, the reduced recovery of potential timber would have implications for carbon storage forecasts, to the detriment of high harvesting scenarios. Indeed, if timber recovery is lower in reality, carbon storage in products will be reduced, which will accentuate the differences between the Ecos, R60 and R95 scenarios.

According to this scenario and the parameters detailed in Chapter 4, managed forests **generate a sustainable timber stock of 0.43 Gm³ between 2020 and 2050, which corresponds to 0.40 GtCO$_2$eq**. This stock comprises 48% hardwood, 48% softwood and 4% poplar.

### 5.5.4. Arbitration in the use of wood harvested for industry or for energy generation

Of the 44.5 Mm³/year destined for energy generation between 2020 and 2050, major conflicts in use are likely to arise between traditional outlets for wood harvested for industry or for energy generation (paper, panels, wood energy, stakes and poles, wood-based insulating materials) and its emerging uses ("advanced" wood-based biofuels, biogas and wood-based chemistry). However, we have seen that potential timber is already being partially used as wood for industry or for energy generation. Additionally, some studies estimate that the proportion of timber in the total harvest could increase further to exceed 50% (Angerand et al., 2014), which seems logical if forestry is improved.

In an ambitious scenario of bio-based renovation/construction, the volume of wood needed to manufacture wood panels in 2050 is estimated at 24 Mm³ of sawable wood for 7 Mm³ of construction panels and 2 Mm³ of insulating panels (Angerand et al., 2014). The potential timber harvest estimated above is therefore necessary, as are the 5 Mm³ (15% of wood harvested for industry or for energy generation) intended for sustainable uses of WIWE. There are fears that not only will potential timber not be used to its full potential, but that the proportion "wasted" on wood energy and emerging uses will increase. However, directing forestry towards WIWE production would clearly run counter to the cascading use and improvement of French forests (Pro Silva France, 2012a; World Wide Fund for Nature (WWF), 2016).

## 5.6. Outlook 2050–2100

Forecasting the changes in stocks beyond 2050 is even more difficult than for the 2020–2050 period owing to climate uncertainties, particularly those related to how society is currently influencing the climate. However, by using clear assumptions to examine the outlook, we can visualise the potential influence of essential parameters in the long term. For this reason, we ran the production/harvest/mortality (PHM) model for continuous cover forestry situations, assuming that current gross production will be maintained and that mortality will stabilise at its 2050 level. It is within this specific framework that the three management situations are studied and presented below. We have not included the substitution effect because its evolution depends on an even greater number of parameters. For soil carbon storage (SCS), we have assumed that beyond 2050, the sink will decrease by 1% per year, stabilising in around 2200 at approximately 412 $tCO_2$eq/ha.

In natural forests, the annual mortality rate would stabilise at 1.63%, with an annual contribution of 5.34m³/ha/year. By 2100, total storage would still be growing significantly, so we have shown the simulated change at 2200. Under these assumptions, the living biomass sink would remain stable until 2100, and the total sink would not reach zero before 2200; total storage would reach an asymptotic plateau in around 2200, with 641m³/ha of above-ground living biomass for 328m³/ha of stemwood (blue line, values on the right), 231m³/ha of above-ground dead wood and 127m³/ha of below-ground dead wood. Of course, the value and timing of the stabilisation of the mortality rate depend on climatic and biotic changes, so these figures are simply indicative. However, this simulation suggests that French forests are far from achieving a balance between production and mortality and a zero-carbon sink.



Scenario NF-M1: Biomass and SW storage (m³/ha) + soil storage ($tCO_2$eq/ha)
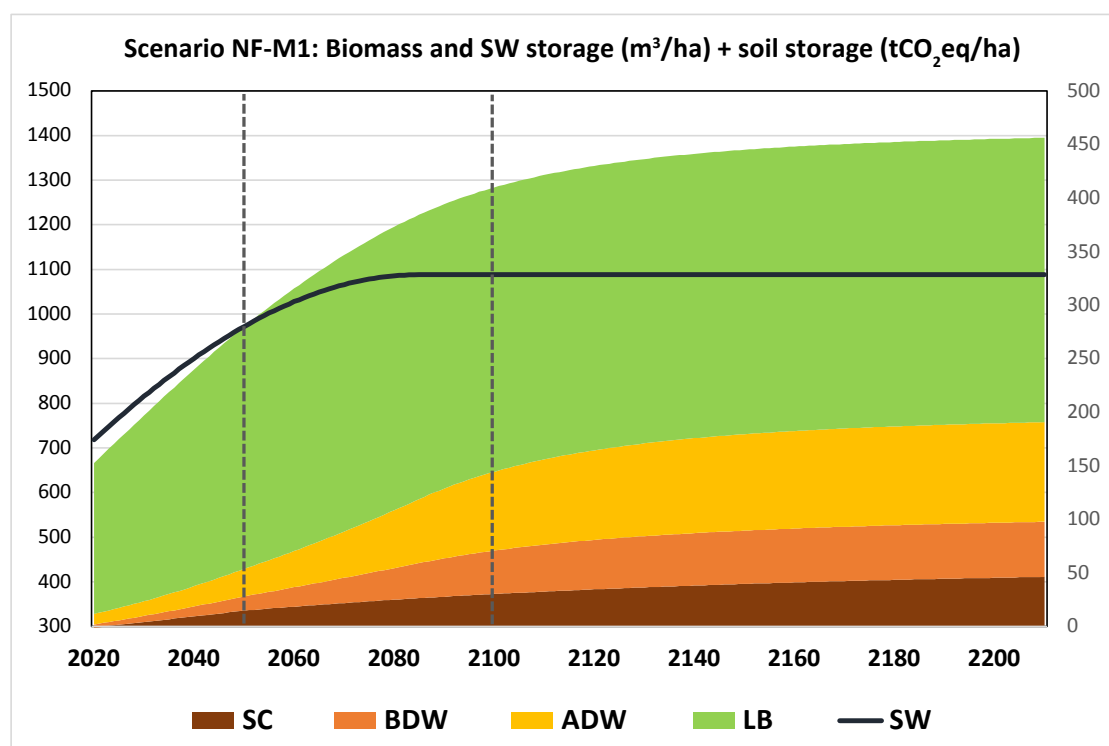
<u>In forests managed under the R60-M1 scenario</u>, the mortality rate would stabilise at 0.61% from 2050 onwards and the trend illustrated in the below graph would occur. It is immediately obvious that wood harvesting markedly accelerates the onset of the asymptotic plateau, setting the maximum level, which it reduces despite the lower mortality rates assumed in managed forests. While the parameters chosen are debatable, in any case this graph indicates that French forests in 2019 are not "over-capitalised and ageing", as they are sometimes presented in relation to natural forests.
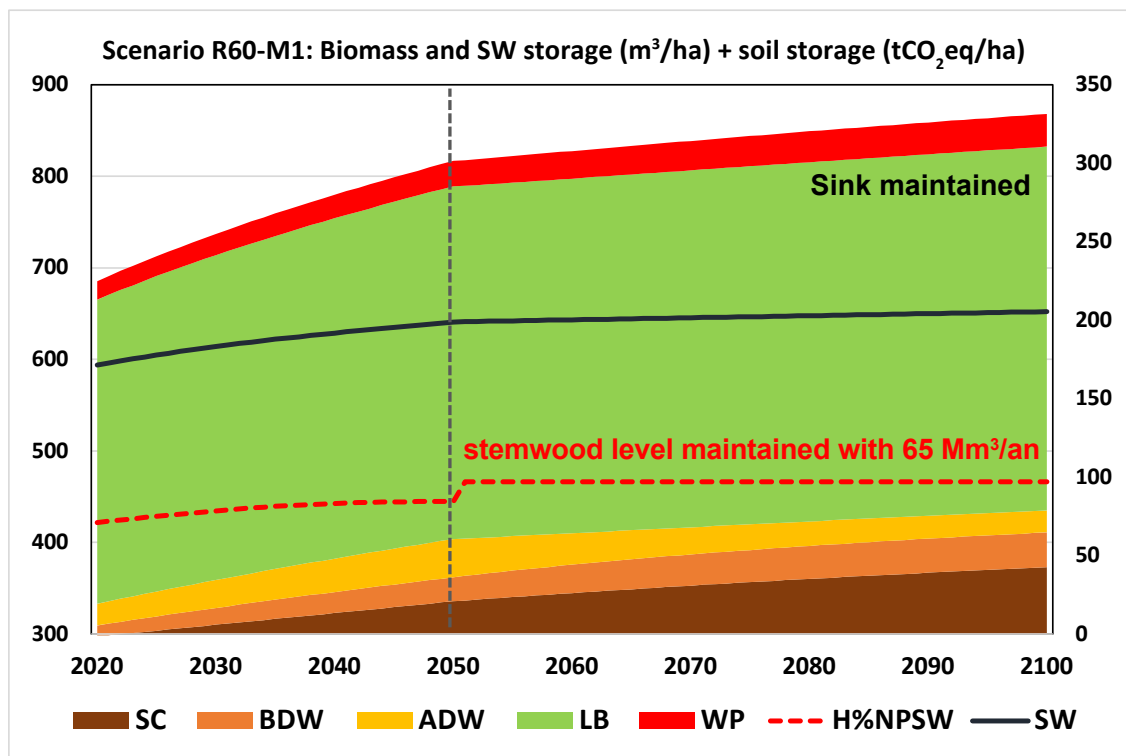


*Legend: storage pools and colour codes: like the other graphs, see legend at the top of this chapter; H%NPSW = harvest rate of net production of stemwood (%); SW = level of stemwood ($m^3$/ha).*

Under the above assumptions, harvesting could increase until it reaches stock in equilibrium, then increase to 97% of net production by maintaining this level of stemwood, without changing the rates of branch and dead wood harvesting in order to respect soil fertility and biodiversity. Harvesting could then increase to 65 $Mm^3$/ year with no variation in storage if mortality does not increase. In 2100, stocks would comprise 398 $Mm^3$/ha of living biomass, 24$Mm^3$/ha of above-ground dead wood, 40 $Mm^3$/ha of below-ground dead wood and the equivalent of 47 $Mm^3$/ha of wood products, or 560 $Mm^3$ for France. Total storage would continue to increase below ground in the soil pool, and secondarily through sustainable products. An average timber lifetime of 200 years would increase the stock of products to 68 $Mm^3$/ha at equilibrium (820 $Mm^3$ for France), which is 15% of the total stock not including the soil pool, or 9% of stock ($CO_2$eq) when soil is taken into account. Even with very long lifetimes, the contribution of wood products and even their management is minor compared to that of biomass.

This positive trend in harvesting would be possible if harvesting were distributed evenly among managed forests. As we have seen, given the current unequal distribution of harvesting, this would most likely require a temporary reduction in harvesting in 2020–2050 from the easiest-to-exploit forests (state-owned forests on plains and large private forests with easy access) while they "caught up" with newly managed forests.

With a rapid change in mortality rates (M2), a harvest of 60 $Mm^3$/year could not be maintained beyond 2050 without a drop in the volume of stemwood per ha, unless more branches and/or dead wood were harvested.

The Ecos scenario is a natural intermediate between these two trends. Although this scenario is ecologically very relevant, we have not gone into more detail here because it seems it would be very difficult to apply in the future (crisis in the sector, loss of jobs mainly in fragile rural areas, increase in wood imports, etc.).

For scenario R95, following the same trend in terms of mortality as in scenario R60 produces the following graph.



Scenation R95-M1: Biomass and SW storage (m³/ha) + soil storage (tCO₂eq/ha)
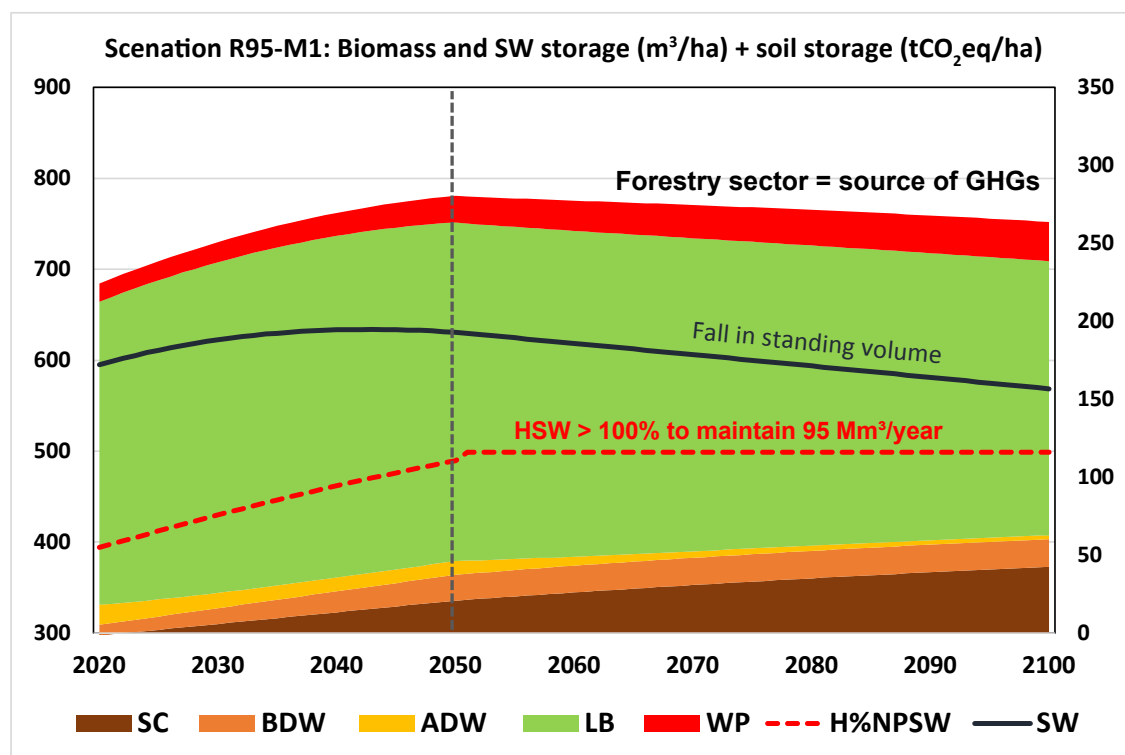
Between 2020 and 2050 harvesting reaches 95 Mm³, exceeding net production. Then, to maintain this level of harvesting, it would be necessary to gradually destock French forests to reach a volume of 168 Mm³/ha of stemwood in 2100, which would fall further after this date if that harvesting rate was maintained. Despite the maintenance of soil storage, this R95 scenario would lead to the gradual disappearance of the entire sink. With this in mind, by 2100 the (un-stabilised) storage would consist of 325 Mm³/ha of living biomass, 5 Mm³/ha of above-ground dead biomass, 34 Mm³/ha of below-ground dead biomass and 53 Mm³/ha of wood products. Wood product storage exceeds that of the previous scenario, but the losses in the other pools are much higher.

This intensive scenario (R95) would have significant consequences for ecosystems, because it requires:

– increased harvesting of branches and natural dead biomass, which can significantly impact biodiversity and soil fertility (Achat et al., 2015a-2015b, see Chapter 2), especially since the majority of productive forests in France are located on acidic soils (IFN, 2015);

– a very low level of storage from above-ground dead wood, which would be clearly lower than the thresholds necessary to preserve biodiversity (Vallauri et al., 2010) and to promote the biological control of parasites and pests;

– a reduction in harvesting limits to maintain a rate of 95 Mm³/year, and therefore the loss of large- and very large-diameter timber in forests, with known consequences for ecology and the landscape, in addition to difficulties with natural regeneration that greatly hinder continuous cover forestry;

– harvesting that exceeds net production from around 2044 onwards to compensate for mortality, which would result in a gradual decline in standing volumes, thus weakening ecosystems and hindering continuous cover forestry, probably necessitating planting in most managed forests.

The R60 scenario could thus represent an interesting compromise between society's needs and preserving ecosystems and their carbon sinks. In this scenario, maintaining the current harvesting level does not mean that very few forests in France could be subject to additional harvesting, but rather that the increase in harvesting in some unmanaged forests (with any obstacles removed) should be offset by a decrease in already intensively harvested forests. This balancing would only be possible gradually and following efforts to group together and equip managed areas so as to expand them. Indeed, it should be recalled that all the scenarios studied in this report assume an increase in managed areas from 65% in 2020 to 75% in 2050, so their application over 1.6 Mha would require significant effort in terms of equipment (roads and tracks) and the resolution of land tenure barriers (regrouping and/or land consolidation, communication, management aids, etc.).

## 5.7. Summary of determining factors for the sink

This sections seeks to summarise the factors that influence the role of forests and wood in mitigating climate change.

After increasing in surface area and volume for nearly two centuries, French forests are gradually moving towards an asymptotic equilibrium in their level of biomass per hectare. However, the volume per hectare at equilibrium (maximum) and the time required to reach it are unknown and will depend on several factors.

The most decisive parameters for storage change for constant gross production are harvesting and mortality rates, which seems obvious given the basic equation for the change in living biomass ($dLB = P - H - M$). However, stocks also include a dead wood (DW) and a wood products (WP) pool, so that:

- for a given mortality rate, the storage provided by dead wood depends on its decomposition time in the forest, and therefore on the nature of the dead wood and the forest microclimate (Hagemann et al., 2010, Vanderhoof et al., 2012);

- for a given harvesting rate, the storage provided by wood products depends on their lifetime in the sector.

However, storage in products will only be really significant in the long term (>2050), while destocking in the ecosystem by means of harvesting and, in particular, total replacement (deadlocks) occurs in the short term. A higher harvesting rate will increase storage in products but will decrease it in the ecosystem. It will therefore be beneficial only if the lifetime of the products is very high, and even greatly exceeds the survival time of the harvested trees, which seems difficult to achieve in theory. The option chosen for deadlocks (replacement) massively destocks the ecosystem and can only be justified in the event of dieback leading de facto to a short lifetime for the wood in a forest.

The upper limit for standing volumes and the respective proportion of dead and living wood in stocks are closely linked to the harvesting (stem and branches) and natural mortality rates used. Harvesting can be adjusted by forest managers to preserve capital (volume and microclimate), but mortality will be determined mainly by climate change, although cutting can influence it. A strong and rapid increase in mortality could increase deadlocks (scenario M2), while a moderate and gradual increase could be tempered by the microclimate of the maintained forest cover, at least up to a defined threshold.

According to our calculations, even in a favourable climate scenario (RCP 2.6), mortality rates increase geometrically to reflect the increase in inter-individual competition for (limited) resources. However, the search for new root spaces, the complementarity of niches and positive relationships between individuals and species could delay this increase in the mortality rate, and in turn the equilibrium phase. Moreover, mortality in m³/year increases significantly only where there are high volumes/ha. It therefore remains to be seen whether, in the long term, careful forest management can truly reduce mortality rates by limiting competition between trees, which would make it possible to obtain a high maximum volume despite harvesting. While this "beneficial"

effect may seem obvious to many foresters, it is not a biological given. "Active" forestry, which has been promoted in many regions over the past 30 years, could even make stands biologically fragile by placing them under stress, even if the trees are physically more stable. To study these factors, it would be worth comparing mortality rates in scenarios where there is no harvesting, where there is "soft" harvesting (in forests where competition is high) and where there is intensive harvesting (that increases the distance between trees).

**In summary**, the climatic relevance of harvesting to stock changes must be studied with regard to gross production, harvesting and mortality rates, and decomposition times in the forest and products' lifetimes. In the long term, changes in soil fertility and biodiversity may also affect biomass by impacting productivity and ecosystems' capacities to regulate their health. Strategies must therefore take into account all these parameters.

The influence of these factors on carbon storage can be summarised as the effect of increasing each of the parameters (with the others assumed to be constant). The results of the substitution are in brackets:

| Increasing parameter | | LB | DW | WP | MD | Sink total | Other effects |
|---|---|---|---|---|---|---|---|
| Biomass production (P) | | ↑ | → | ↑ | (↑) | ↑ | Fertility (–) |
| Biomass mortality (M) | | ↓↓ | ↑ | → | → | ↓ | Biodiversity (+) |
| Harvesting | Stem ($H_{sw}$) | ↓↓ | → | ↑ | (↑) | ↓ | Fertility (–) |
| | Branches ($H_{br}$) | → | ↓ | → | → | ↓ | Fertility (–) |
| | Mortality ($H_m$) | → | ↓ | → | → | ↓ | Biodiversity (–) |
| Decomposition time of dead wood (DT) | | → | ↑ | → | → | ↑ | Biodiversity (+) |
| Timber product lifetime (PL) | | → | → | ↑ | (↑) | ↑ | Depend on the case |
| Emissions upstream of the sector | | → | → | → | ↓ | ↓ | Depend on the case |

**To store as much carbon as possible in the forest/product system, it is in our interest to:**

1. Reduce natural mortality as much as possible by avoiding micro-climatic shocks, damage to above-ground bodies, root stress, physical and chemical soil erosion and monocultures that are vulnerable in terms of health;

2. Increase the decomposition time of dead wood by stabilising the micro-climate;

3. Increase product life by optimising cascading use;

4. Limit harvesting, particularly of branches (no stump harvesting);

5. Reduce emissions from the sector to maximise material displacement factors.

## 5.8. Comparison with other scenarios

Several recent studies (Valade et al., 2017; Roux et al., 2017; Martel et al., 2018; ADEME et al., 2018) have shown the negative effect of increased harvesting on carbon storage in France. This common observation therefore raises serious questions about programmes that increase harvesting in terms of the role of forests in mitigating climate change.

As explained in chapter 3, the current level of harvesting, estimated at a total wood volume of 60 Mm³, excluding operating losses is based on the analysis of annual branch surveys for marketed volumes, an estimate of wood volumes consumed by harvesters and an estimate of operating losses. With an estimated 10% margin of error, this total harvesting breaks down into 20 Mm³ of timber, 11 Mm³ of wood harvested for industry, 8 Mm³ of

marketed wood energy and 21 Mm³ of wood energy not counted in the branch survey (FCBA, 2018). The WIWE/TIM ratio is estimated at 1.65. However, since the 2007 Grenelle Environment Forum and President Sarkozy's speech in Urmatt in 2009, the opportunity to significantly increase harvesting has guided forest policies. Several recent studies (ADEME and MAAF in 2009, and the Directorate General of Energy and Climate (DGEC) in 2014) affirm that French forests could (or should) withstand a significant increase in harvesting. In 2014, the Act on the Future of Agriculture, Food and Forests established a new forest policy framework with the National Wood and Forest Programme (Programme National Forêt Bois, PNFB in French). Based on the argument that French forests are under-exploited, this programme sets a target of extracting 72 Mm³ of wood by 2026 (PNFB, 2016), which is in just seven years' time.

An initial National Low Carbon Strategy was adopted in 2015 (MTES, 2015), and is currently being revised (MTES, 2018a). In the current version of the strategy, the forest carbon sink (excluding soil and products) in 2014 was estimated at around -65 $MtCO_2eq$/year. By 2050, it would fall to -85 $MtCO_2eq$/year for the "with constant measures" scenario (without any change in practices) and to -54 $MtCO_2eq$/year for the scenario with intensification measures, giving a gap of 31 $MtCO_2eq$/year between the two scenarios. In the draft National Integrated Energy and Climate Plan (MTES, 2019), the forest carbon sink is estimated to be -32 $MtCO_2eq$/year by 2050, which is half the current sink.

Neither the National Low Carbon Strategy nor the draft National Integrated Energy and Climate Plan specify the relationship between the reduction in the carbon sink and increased wood harvesting. However, they do acknowledge that "meeting national objectives for developing renewable energies will in any case require a massive increase in forest wood harvesting (National Low Carbon Strategy, second draft, 2019) and "a five-fold increase in the use of non-food biomass by 2050" (MTES, 2019). The 2019 draft strategy proposes continuing to increase the harvesting planned for between 2016 and 2026, reaching 81 Mm³/year in 2035 and 93 Mm³/year in 2050. By 2050, the total harvest could therefore reach around 93 Mm³/year – a level close to our R95 scenario.

The share between material use (sawable wood or panels) and energy generation is also not specified in the National Low Carbon Strategy or the National Integrated Energy and Climate Plan. However, the National Forestry Accounting Plan (CITEPA et al., 2018) specifies that 34% will be used as solid wood and 66% for energy generation purposes, producing a WIWE ratio of close to 2. This would therefore represent a significant increase in the proportion used for energy generation, which could be interpreted either as a sign of a sharp decline in the availability of timber owing to changes in health and/or forestry practices, or as a result of diverting a significant proportion of timber to energy generation, or the two vectors combined.

The forestry measures to be put in place to obtain this growth in harvesting are not specified, but from our study we can deduce that in this vision of the future:

- forest stocks and the total carbon sink will decrease significantly;
- the volume of stemwood in 2050 will be far from stock in equilibrium that enables continuous cover forestry, which could nevertheless optimise long-term production and the multifunctionality of forests (AFI, 2010);
- at least three quarters of the volume of branches and dead wood will be harvested, which is likely to reduce soil fertility and biodiversity (see Chapter 2);
- the WIWE/TIM ratio will increase from 1.65 to 1.94, suggesting an increasing use of potential timber as WIWE, unless dedicated WIWE forestry is introduced in some areas of French forests;
- lastly, the age at which trees are able to be harvested will likely be lowered continuously – as these reports often mention – which would not improve the total carbon sink and would have grave consequences for biodiversity and soil fertility.

These current strategies to increase harvesting, far from improving carbon storage in French forests, would instead reduce the sink while putting soil fertility and biodiversity at risk, as well as, in all likelihood, creating conflicts of use that would not improve the image of forest exploitation in the eyes of civil society.

# 6. STUDY CONCLUSION

Through this study, we have attempted to provide a deeper understanding of the evolution of the carbon sink represented by forests and the wood sector, in order to propose a strategy to optimise the role of forest management in mitigating climate change by 2050.

To set out the specifics of this strategy and study its potential impacts, we first identified three typical management contexts in Metropolitan France (natural forests, deadlocks and continuous cover forestry). Areas where continuous cover forestry cannot be applied in the short term (deadlocks) have been the subject of a reforestation plan that specifies the species to be used and their proportions. Then, three harvesting scenarios are defined, based on very different objectives (prioritising the sector, prioritising the ecosystem, and a compromise), assuming a constant surface area (16 Mha), and in two scenarios with different annual mortality evolution trends, which can be linked to optimistic (RCP 2.6) and pessimistic (RCP 8.5) climate projections. The study ensures that each scenario is consistent, limits variations in the fundamental parameters not studied (pathways by management context, wood recovery) and avoids judging the behaviour and skills of the forest managers who implement the scenario. These parameters are likely unique to this study when compared to other in-depth and now influential studies (Roux et al., 2017). However, the methodology chosen will always have limitations, which we have discussed throughout the text.

The scenarios studied lead to total annual harvests in 2050 that range from 30 to 95 Mm$^3$, a result of differing trends in the harvesting rate for stemwood and for branches and trees that have died naturally.

Natural forests show the best potential for mitigation between 2020 and 2050, including when product stocks and substitution effects (emissions avoided) are considered. The "extensive" scenario optimises the development of stocks in the ecosystem, while the "intensive" scenario optimises the development of stocks in wood products. However, from an equal initial state in 2020, total storage (ecosystem + products) in 2050 is significantly larger when harvesting is low. The sink (annual flow) decreases continuously in the scenario that involves increased harvesting, while it increases when harvesting decreases. In 2050, the average total sink per hectare in the intensive scenario is almost half that of the scenario for natural forests.

In the light of current knowledge, these changes in storage will most likely have consequences not only for biodiversity, but also for soil fertility and thus the ability of ecosystems to continue producing wood without becoming dependent on energy-intensive and likely-polluting inputs. In the long term, increasing harvesting to 95 Mm$^3$/year would lead to a gradual decrease in standing volumes, which would significantly reduce the carbon sink, increase stands' vulnerability to climate hazards and affect forests' natural regeneration capacities. It is likely that this would lead to an increase in the proportion of deadlocked forests, thus favouring plantation forests and even-aged high forests.

Beyond issues of ecological sustainability, rapidly increasing harvesting as in our R95 scenario would require authoritative measures to utilise managed areas and standing volumes. Conversely, a reduction in harvesting, as in the Ecos scenario, could trigger a supply crisis in the wood sector, worsening sawmill closures and employment problems in rural areas and leading to increased imports. The scenario in which current harvesting is maintained seems an attractive compromise, provided that harvesting distribution gradually improves.

We therefore propose an enhanced mitigation strategy based on: (1) making an explicit decision to leave 25% of the forest area to evolve naturally, with 10% of this strictly protected under a legal framework; (2) continuing

to harvest at 60 Mm³/yr until 2050, increasing the managed area to 75% to provide better spatial distribution of this harvest, achieve a stock in equilibrium, and reduce harvesting rates of branches and dead wood.

It should be remembered that these scenarios are established at the national level while, within a defined policy and legal framework, forest management is organised at the regional level, and technical decisions are made at the local level. Changes in our forests will thus be the result of the addition of micro-decisions made by owners and their technical partners, under the scrutiny of civil society. The latter is likely to call for a review of public policies at both the local and national levels, and also to support and assist owners and their partners as they advance towards good practices. Beyond the State's responsibility to define national policies, each party will therefore participate in providing concrete guidance on forest management. Along with this responsibility, we are all responsible for the current state of our forests, and for the worrying changes seen in the climate, which the forest alone cannot contain.

The subject matter is very complex, and our study is far from exhaustive or definitive. It is not intended to answer the urgent questions raised today by climate change, the role to be played by forests and wood products, and the growing conflicts between the functions of forests in metropolitan areas. Its fundamental role is to demystify, at least in part, the knowledge and calculations necessary to understand and simulate changes in carbon stocks and sinks under different management scenarios. By ensuring that we are rigorous and transparent, we have built a tool for reflection and evolving dialogue, which is open and free from taboos, which we hope will help in jointly designing a truly multifunctional management plan for French forests between 2020 and 2050.

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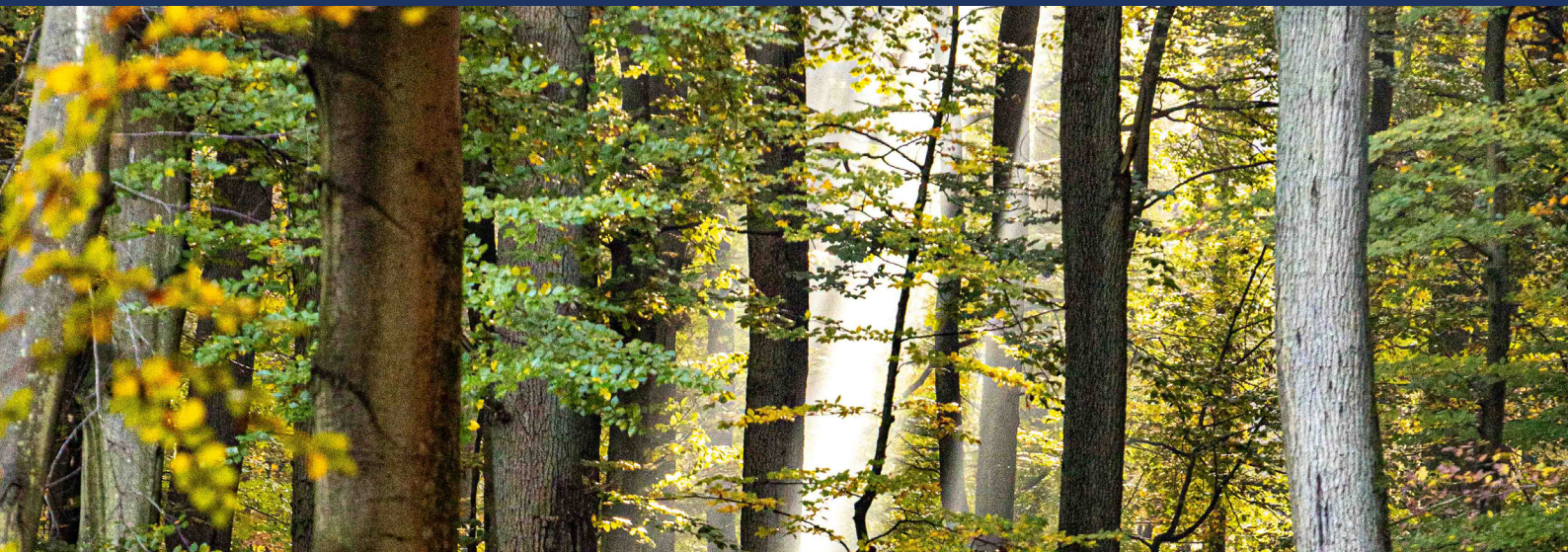
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