THE ROLE OF FRENCH FORESTS AND THE FORESTRY SECTOR IN CLIMATE-CHANGE MITIGATION

OPPORTUNITIES AND DEADLOCKS BY 2050

SUMMARY OF A STUDY CONDUCTED BY INRA AND IGN
FOR THE MINISTRY OF AGRICULTURE AND FOOD - JUNE 2017

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Carbon sequestration and the reduction of greenhouse gas (GHG) emissions, as strategies to limit climate change, are objectives of the highest global importance, deserving close study by every nation. Forests and the forestry & wood sector are recognized as strategic elements in the question of climate change mitigation due to their large capacity for carbon storage and their potential to limit GHG emissions. The overall carbon impact of the forestry sector includes both the effects of carbon storage in forest ecosystems and forestry products, and a substitution effect that can result from the use of wood in place of other materials or energy sources that are greater emitters of GHG. In this context, the French Ministry of Agriculture and Food requested INRA and IGN to conduct a study of the GHG emissions mitigation potential of the forestry-wood sector in France through the year 2050. The scope of the study included all forests available for wood production in mainland France, all wood-processing industries, and all social actors contributing to the development of the bioeconomy via *this primary production and processing supply chain.*

Using simulations of the effects of three contrasting forest management scenarios through the year 2050, the study confirms the central role of the French forestry & wood sector in climate change mitigation. In addition to carbon storage in forest biomass, significant benefits could be gained through increased use of wood as an energy source and – more importantly – as a material. The latter strategy, which could be encouraged through proactive forestry management and tree-planting programs, is likely to become more important as climatic conditions deteriorate and as forests become increasingly subject to severe weather events and associated threats such as forest fires and pest outbreaks.

Four aspects of the forestry & wood sector enable action with respect to climate change: (i) carbon storage in forest ecosystems; (ii) carbon storage in wood products; (iii) substitution effect from the use of wood materials in the place of non-wood materials; and (iv) substitution effect from the use of wood energy in place of fossil energy. Forestry-sector policies and practices influence all four of these aspects. It is worth considering which strategies favour carbon storage in forest ecosystems via reduced tree harvesting; and conversely which strategies favour substitution effects and carbon storage in wood products via stimulation of tree harvesting and the use of wood-sector outputs.

Carbon storage in the French forestry sector: The current situation

The first step in assessing the carbon impact of France's forestry sector with regard to these four action mechanisms was to conduct a review of the extensive international scientific literature on the subject. Our primary goals here were (i) to identify and refine the relevant assumptions and coefficients with respect to carbon storage and substitution effects, as applicable to the French national context; and (ii) to identify points of uncertainty and evaluate how these affect key parameters.

Carbon storage in forest ecosystems results from forests' capacity to absorb atmospheric CO_2 and retain it in living biomass aboveground and belowground, in deadwood, and in forest soils. Forest dynamics – influenced by such factors as stand age, management methods, climate, weather events, and pest pressure – are critical to this capacity.

Carbon storage in wood and wood-based products depends on forestry yields, the uses that are made of wood, and the lifespan of the products or materials in question.

Energy substitution relates to the quantity of CO_2 emissions avoided by using wood energy in place of a reference energy source (oil, gas, coal, electricity from multiple sources, national grid, etc.)

Product substitution relates to the quantity of CO_2 emissions avoided by using wood instead of other materials (concrete, steel, plaster, aluminium, etc.) in key sectors such as construction.

Accounting for substitution effects is central to understanding the role of forests and forestry products in climate change mitigation. Doing so is challenging, however, because it requires comparing supply chains for each product, from primary materials through to eventual disposal, according to the principles of Life Cycle Analysis. Substitution coefficients are thus specific to a given national industrial context.

By adapting carbon storage and substitution effect coefficients drawn from the international literature to the current situation in France, we can convert material flows between different stages in the French forestry & wood sector (expressed in Mm^3/year) into fluxes of CO_2 equivalent relative to the various mitigation mechanisms (expressed in $MtCO_{2eq}$/yr) (Figure 1).

Currently, the sector's net carbon impact is dominated by carbon storage in forest ecosystems, estimated at 88 $MtCO_2$eq/yr. The largest portion of this is in above- and belowground biomass of hardwood stands. Carbon storage in biomass of softwood species, in deadwood, and in soils also plays a role, but at much lower amounts. Annual storage *via* the use of wood products is considered to be nil, meaning that at present, the amount of carbon stored in wood materials produced in a given year is equal to the amount of carbon released at the end of materials' life or through the destruction of older wood products. The favourable impact of wood product use thus only comes into play through substitution effects. Substitution effects from the use of wood materials are significant (32.8 $MtCO_2$eq/yr according to our assessment), while substitution effects from the use of wood energy have little impact on the sector's total carbon budget.

Forest management decisions and the future development of the timber industry – notably with respect to harvest intensities, replanting cycles, and product use – will directly influence the sector's carbon impact. Key factors include forest stand dynamics and their capacity to store or release carbon, as well as the sector's capacity to market products that can successfully compete with rival materials. Maintaining low harvest levels allows for additional carbon storage in forests as long as stands are healthy and growing, but limits further development of the bioeconomy and thus the potential substitution effects resulting from an increased use of wood products. Minimal harvesting may also leave forests more susceptible to weather events and at a potentially greater risk of losses to pests and other threats. More aggressive harvesting, on the other hand, accompanied by a more rapid turnover of tree populations and a policy of climate-change adaptation, would temporarily reduce carbon storage in forests, but this effect would be compensated for, at least in part, by a reinforcement of substitution effects further down in the supply chain. By strengthening the forestry-wood sector, the latter strategy would help develop the bioeconomy and offer associated advantages in terms of job creation and economic growth.

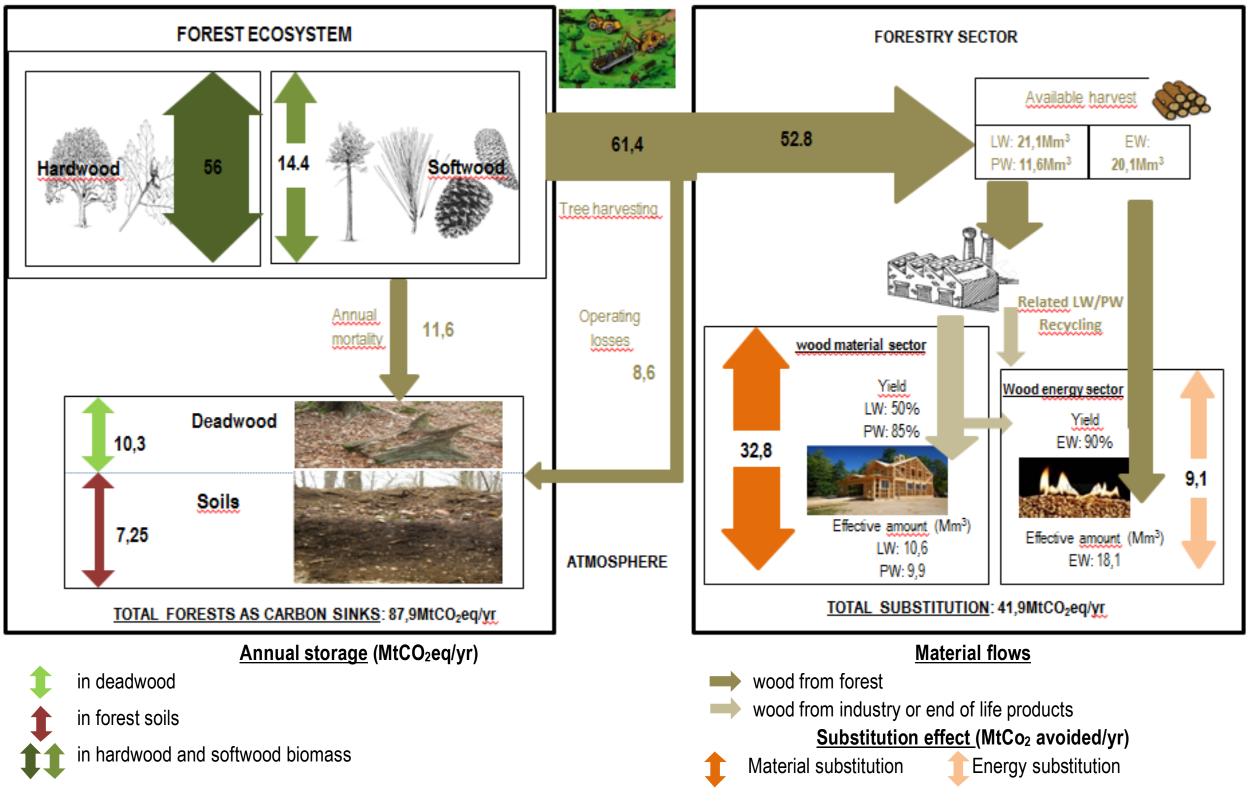

Figure 1 – Flows of material and CO_2 at different stages of the French forestry & wood sector in 2013
(TAV= Total aboveground volume, LW=Lumber, PW=Pulpwood, EW=Energy wood)

NB: The variation in carbon levels in wood products is estimated at 0 and -0,1 $MtCO_2eq/yr$ for LW and PW respectively, and thus does not appear in CO_2 fluxes for the sector in 2013

Three forest-management scenarios to enhance climate-change mitigation potential

To assess the effectiveness of different strategies in enhancing climate change mitigation in the forestry & wood sector, three contrasting management scenarios were simulated, using three complementary modelling tools (see Box, p. 5). The models allowed for the integrated analysis of: forest resource dynamics (variable according to the effects of climate change and other challenges to forest health); harvesting intensities; and the use of wood products. The three management scenarios were differentiated according to their relative emphasis on forests as carbon sinks, carbon storage in wood products, and substitution effects resulting from wood use.

Scenario 1: Extensification and reduced harvesting

In this scenario, societal preferences for more "natural" landscapes combined with weak prices and policy signals lead to trends of extensification, with large forested areas left unmanaged or only minimally managed. Forests in mountainous and Mediterranean regions receive minimal management, while forests in the Massif Central are under-utilized. Forest managers allow forest ecosystems to adapt to climate change through spontaneous evolution.

The total national tree harvest remains close to its current level (50 Mm^3 TAV/yr), amounting to **a reduction in logging rates from 50% of net biological growth, to 42% in 2035 and 37% in 2050**. There is a continued gradual loss of large-diameter hardwoods for wood-energy markets. A lack of specialised machinery for hardwood felling combined with a deterioration of hardwood timber quality and quantity lead to an increased focus on softwood species.

With the exception of the Landes forest, forestry practices in this scenario are based on natural regeneration. Given an absence of active management in the majority of mainland forests, continued rapid capitalisation (as observed over the past 30 years) and an increase in carbon sinks are expected. At some point, however, aging and density of stands may lead to a loss of available wood resources and of carbon storage capacity in forests.

Scenario 2: Territorial dynamics

This scenario is characterised by regional pressure and other developments that prompt sector actors to adopt strategies and policies specific to their local area, with significant decision-making taking place at the regional level rather than at the national level. A key driver in this scenario is a strong demand for biomass, especially for energy. Low prices nevertheless lead to a simplification of management practices and a specialisation of management objectives. Industrial wood usage is penalized by the strong demand for wood biomass for energy, especially heating systems. Management strategies remain extensive in some regions, however, notably in high mountain areas and around the Mediterranean. Forest managers and timber processors are aware of climate risks, but other constraints – economic, sylvicultural, and environmental – allow them little opportunity to modify their practices.

Harvest levels remain at current rates for the entire period (averaging 50% of net biological growth), with **total harvest volume thus increasing to 75 Mm^3 TAV/yr by 2035**. New strategies for making use of hardwoods are developed thanks to the investment capacity within the French timber industry that can be increased thanks to the involvement of foreign companies buying wood on contract. Investment in forests is uneven, however, with modest development of woodlot access and an increase in logging found only in those regions where downstream demand and local policy initiatives work together to bring about such changes.

Scenario 3: Intensification and active replanting

This scenario assumes an economic and political context favouring a rapid transition toward a new "bioeconomy." Use of hardwoods is facilitated by technological innovations, investments in forestry and timber industry infrastructure, changes in consumer behaviour, training and education programs, strong public incentives for property consolidation, increased use of contracts, and simplification of planning policies. This combination of forces supports greater investment in forests, with strong markets for wood products and a more favourable tax regime. This situation results in turn in more active forest management, including the implementation of diverse strategies for climate-change adaptation (strengthening and protecting ecosystem services, improving sector resilience to shocks from extreme events).

Forests in mountainous areas are partially brought back into production, while Mediterranean forests provide more energy-wood, pulpwood, softwood timber and potentially even small-diameter hardwoods. Forestry management methods shift in favour of harvesting of younger stands (allowing for reduced risk and the use of processing methods for smaller-diameter trees) in the Landes forest and other regions. Strategies foster diversification of these forests in terms of both tree species and age class.

A specific **replanting plan** is implemented in this scenario. It involves large areas that are already forested but are currently unproductive or not economically viable. The stated objective is to replant 50,000 ha/yr for the next 10 years, or a total of 500,000 ha. These plantings have a major impact on total forestry output in terms of both quality and quantity, thanks to the diffusion of new, highly productive varieties (softwoods, poplars) from breeding programs reoriented to address the impacts of climate change and the requirements of the bioeconomy.

The national harvest increases (more in some regions than in others), **moving toward an average logging rate of 70% of net biological growth by 2035** and remaining stable thereafter. This gradual but significant increase requires a corresponding growth in capacity within the relevant timber-industry sub-sectors (nurseries, primary processing in France, secondary and tertiary processing).

Biodiversity and ecosystem services in the three scenarios

Tangible benefits with regard to biodiversity and ecosystem services can be expected in all of these scenarios, although the nature of these benefits will vary. Expanded biodiversity monitoring would be useful in all three scenarios to verify anticipated benefits and detect any signs of deterioration.

Strategies to expand the forestry sector's role in climate change mitigation

The impact of these three scenarios on the overall carbon footprint of the French forestry & wood sector were simulated through 2050 using the IGN resource-modelling tool known as MARGOT (see Box, p. 5). The three different trajectories result in marked differences in the total volume of wood harvested annually from French forests, corresponding to different levels of intensification. The corollary to increased logging rates is a reduction in standing wood as one moves from the "extensification" scenario to the "intensification" scenario.

Projections for the carbon sequestration capacity of forest ecosystems (forest biomass, deadwood, and soils) in the three scenarios diverge accordingly (Figure 2). The "extensification" scenario results in a considerable increase in annual carbon storage in forest ecosystems, rising to more than 130 $MtCO_2$ eq/yr by 2050. A more moderate increase in carbon storage is achieved in the "territorial dynamics" scenario, reaching less than 100 $MtCO_2$ eq/yr by 2050. Annual carbon storage actually decreases in the "intensification" scenario, a result of increased logging rates through 2035 and the effects of the replanting program.

The replanting scheme leads to an initial drop in carbon storage as a result of concentrated clear-cutting between 2021 and 2030 (Figure 2). This loss is only partially regained in the following decades because the 2050 horizon is too close in time for the benefits of the new plantings to take effect. These benefits will only appear clearly after 2050 and will peak in 2070. The gain from these plantations is lower than might be hoped, moreover, due to the "realist" constraints imposed on the simulated replanting program, including limits of accessibility and limits of economic viability (with the least-productive areas assumed not to be subject to replanting).

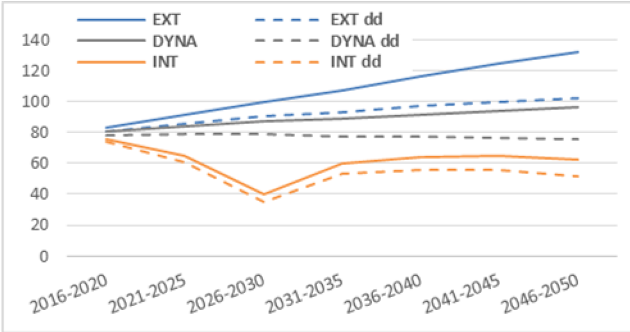

Figure 2: Annual carbon sequestration in forest ecosystems under three management scenarios, with and without "density dependence" effect (dd), current climate, in $MtCO_2$ eq/yr.

This result must be qualified, however, by noting one of the limitations of the MARGOT resource model. This model is based on observed data and simulates the growth of a given number of trees, but does not consider the effects that a significant capitalisation of French forests could have on forest productivity. This could increase sharply by 2050, given the unfavourable effects of stand density on stand growth. Including this constraint in the model ("dd" in Figure 2) produces a substantial alteration in the projected carbon storage capacity of French forests under the three scenarios, with the difference between scenarios being substantially reduced. Growth in annual carbon storage capacity between 2016 and 2050 is only 25% in the "extensification" scenario (compared to +60% without this constraint); annual carbon storage capacity remains stable in the "territorial dynamics" scenario; and the reduction is slightly more marked in the "intensification" scenario.

Carbon storage in wood products and GHG emissions avoided thanks to the use of wood materials and wood energy are also important components of the forestry sector's overall carbon impact. The substitution effect from wood use is consistently positive: it remains steady over time in the "extensification" scenario; increases slightly in the "territorial dynamics" scenario; and increases substantially in the "intensification" scenario (Figure 3A).

Using the assumptions adopted here, total carbon storage attributable to the substitution effect for the period 2016-2050 is thus 33% higher in the "intensification" scenario than in the "territorial dynamics" scenario, and 60% higher than in the "extensification" scenario (Figure 3B).

Again, however, it should be noted that in the current state of research, estimates of avoided emissions are highly sensitive to the substitution coefficients used for wood materials and how these are assumed to change over time. Uncertainty in this regard exists at several levels. The value used here, for both pulpwood (PW) and lumber wood (LW), is 1.6 tCO_2 avoided/m^3 of wood, or the midpoint within the range of values reported in the literature (0.59 to 3.47 tCO_2/m^3).[1] Substitution coefficients for wood materials depend on the specific type of wood product in question as well as on any alternative technologies considered in establishing the reference value, making the result sensitive to the level of precision applied in disaggregated PW and LW products, among other factors.

[1] Sathre, R., O' Connor, J., 2010. Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science & Policy*, 13 (2): 104-114.

Three complementary models for simulating resource and harvest dynamics for forestry systems

The centrepiece of our approach to simulating the effects of various scenarios through the year 2050 was the **MARGOT** model (Matrix model of forest Resource Growth and dynamics on the Territory scale). Developed by IGN, MARGOT allows for a detailed analysis of forest resource dynamics at the regional level. MARGOT is based on "study areas" defined using data collected as part of the National Forest Inventory (IFN), with comparable forest stands grouped together in terms of species, parcel characteristics, environmental conditions, and management features. It combines two demographic models to assess changes in the forest resource: the first describes a stand of trees (excluding poplar plantations) by diameter class (from 5 cm to 90 cm and above) and applies a growth rate for its average volume based on the actual observed growth rate of a comparable stand of the same diameter class. The other is specific to poplar plantations and employs an analogous approach but by age class. Logging rates can be determined from this in several ways. For the "territorial dynamics" scenario, harvest rates were held constant relative to the prior period. For the "intensification" scenario, they were modified to reflect increased logging rates. The "extensification" scenario was based on harvest levels obtained from simulations with the FFSM model.

UMR LEF in Nancy developed **FFSM** (French Forest Sector Model), an economic modelling tool primarily designed for theoretical analyses but calibrated using actual data. It is a multi-modular model, one module of which describes the economic sector in partial equilibrium. Using a set of parameters describing the economic behaviour of different actors (landowners and forest managers, processors, consumers), FFSM creates an output of economic variables relating to supply and demand at different points in the supply chain for the time period requested (prices, volumes proposed and ordered, international trade, surpluses). It thus enables an economic analysis of different scenarios, anticipating, among other things, those public policy instruments that are needed to guide sector dynamics in specific directions.

Finally, to account for the effects of climate change on forest dynamics, we used the **GO+ model**. UMR ISPA in Bordeaux developed this tool which depicts the primary biophysical and biogeochemical processes of a forest ecosystem for specific production forestry species (maritime pine, Douglas fir, and beech). It can be used to model growth, production, and forestry management while allowing for changes in environmental conditions, including climate effects, in the analysis of forest dynamics. Anomalies in growth dynamics highlighted by GO+ in the case of accentuated climate change effects (RCP 8.5) were then introduced into the MARGOT model as parameter modifications: results from the "Beech" model were used for all hardwood species; results for "Maritime pine" for all pines; and results for "Douglas fir" for all other softwoods.

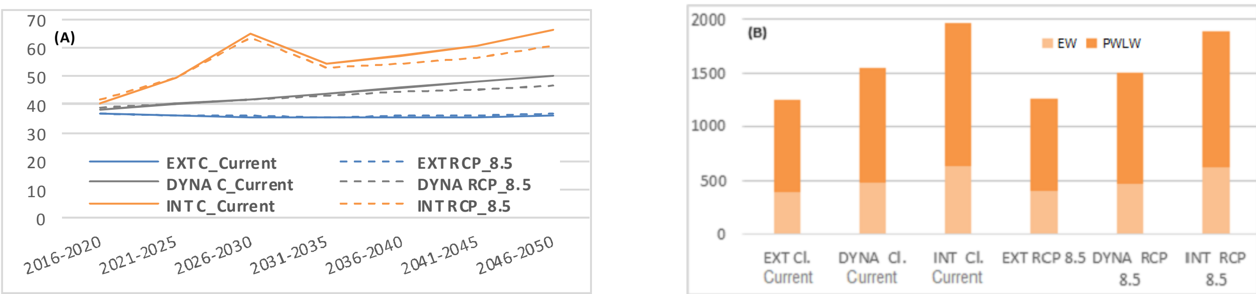

Figure 3: Avoided GHG emissions from substitution effects, using wood products based on three management scenarios and two climate backgrounds, current climate and degraded climate (RCP 8.5).
(A) Annual carbon storage in MtCO$_2$ eq/yr; (B) Cumulative carbon storage from 2016-2050 in MtCO$_2$ eq

Changes in these substitution coefficients through 2050 are likewise difficult to predict since they will depend on the development and performance of technologies in competing sectors relative to future uses for wood products. An increase in the use of wood for construction and a decrease in pulpwood applications (a scenario not considered here), coupled with a small improvement in the environmental impact of rival sectors, for example, could lead to an improvement in these coefficients over time.

Notwithstanding these two important points of uncertainty (long-term changes in forest productivity; determination of substitution coefficients for wood products), the lessons that emerge from the three scenarios described here underscore the key role of France's forestry & wood sector in mitigating GHG emissions through 2050. This role is based on forest ecosystem capacity for carbon storage as well as on the substitution effects (avoided GHG emissions) available through a more widespread use of wood products and wood materials. Carbon storage effects appear to be more favourable in the "extensification" scenario, although they may also be limited by the impacts of stand aging on forest productivity. Substitution effects appear to be more favourable in the "intensification" scenario, and may be further improved if technological innovations can achieve improved substitution coefficients for the use of wood products over other materials.

Efforts needed to expand the use of forest resources

The analysis using the FFSM model (see Box, above) highlighted the economic barriers to increased forest harvesting as envisaged in the "intensification" scenario and (to a lesser extent) in the "territorial dynamics" scenario. If the structure of the forestry & wood sector remains unchanged, and if consumer habits with respect to the use of wood products continue at current levels, it will be both difficult and expensive to use public funding to increase logging activities to maintain current rates of harvesting (the central principle of the "territorial dynamics" scenario). To address this lack of « spontaneous » response of the market, strong economic signals to both consumers and producers would be needed. On the demand side, consumers could be encouraged to see the value of wood and to make greater use of wood products in place of other materials. On the supply side, forest landowners and wood processors could be assisted in developing and marketing wood materials and products that appeal to consumers and that meet specific needs.

Whatever efforts are pursued to increase logging and replanting activities, the potential advantages for the sector as a whole are significant. The economic benefits to consumers, landowners, and timber processors of the "territorial dynamics" scenario are twice those of the "extensification" scenario, for example, not including any impacts in terms of jobs creation (which deserve to be studied in more detail).

Impacts of climate change on forestry-sector carbon dynamics

Another important variable to be considered is the impact of climate change on forest resources over time. The three forest-management scenarios we have outlined will have different impacts on the forestry sector's carbon footprint under different climate conditions. We used average climate data for the period 2003-2013 as the basis for what we refer to here as the "current climate." In 2050, this climate comes with a series of dry years similar to that experienced from 2003 to 2006. This "reference" climate can be compared to an alternative possibility in which climate change effects are intensified (corresponding to the IPCC's RCP 8.5). The impacts of this "degraded climate" on forest productivity were examined using the GO+ model and then integrated into the MARGOT model (see Box, p. 5). Estimates of the effects of drought on tree mortality relied on data from the national forest surveillance network. Under "degraded climate" conditions, a drought of equivalent or greater severity compared to the 2003 drought is foreseeable in the initial quadrennial of 2016-2020, with potential reoccurrence every several years. These conditions are predicted to trigger additional tree mortality, especially for softwoods, affecting single adult trees of medium or large size, without spatial or temporal distinction.

Under these circumstances, and regardless of which of the three forest-management scenarios is followed, the carbon storage capacity of forest ecosystems in France will be significantly reduced (Figure 4). Annual storage will increase by just 30% from 2016-2050 under the "extensification" scenario (vs. +60% in the current climate); will remain nearly level in the "territorial dynamics" scenario (vs. +20% in the current climate); and will fall by 40% in the "intensification" scenario (vs. a drop of 20% from 2016-2050 under current climate conditions).

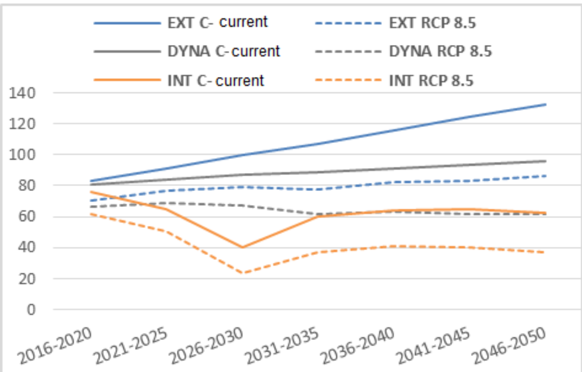

Figure 4: Annual carbon storage in forest ecosystems under three different management scenarios, and under a current climate vs. a degraded climate (RCP 8.5), in $MtCO_2eq/yr$

Impacts on substitution effects will be less dramatic. For the "extensification" scenario, avoided GHG emissions as a result of product substitution will be nearly identical under degraded climate conditions compared to current climate conditions; and they will be only slightly lower for the "territorial dynamics" and "intensification" scenarios (Figure 3A). The estimated total amount of avoided emissions over the 35-year period considered here is only slightly affected by an anticipated worsening of climate trends (Figure 3B).

The reduction in carbon storage in forest ecosystems is potentially overestimated in this model due to our use of beech as a stand-in for all hardwoods, a particularly drought-sensitive species. Impacts on carbon storage under aggravated climate change conditions may also be compensated for by the maintenance of substitution effects. In terms of the total forestry-sector carbon footprint, the impact of degraded climate conditions will be less damaging under scenarios that rely more heavily on the substitution effect ("intensification" and "territorial dynamics") and more damaging in scenarios of the "extensification" type.

Major events that reduce the gaps between different management scenarios

The frequency and intensity of pest outbreaks and weather events that can threaten French forests are likely to increase in the future. Major events such as severe storms, forest fires, or large-scale pest outbreaks may dramatically reduce anticipated gains in carbon storage in forest ecosystems nationwide. To address this possibility, three types of unfavourable incidents were introduced into two of the scenarios described above ("extensification" and "territorial dynamics"): (i) widespread forest fires that overcome containment measures, which are more likely following periods of repeated drought and will therefore increase with the effects of climate change; (ii) severe storms and their attendant risks, including forest fires and bark beetle outbreaks; and (iii) large-scale pest outbreaks causing severe damage to a range of hardwood and softwood tree species.

Drought followed by forest fires

Periods of drought considerably increase the risk of forest fires, as was the case in 2003, when nearly 75,000 hectares burned. To measure the impact of such events on the total carbon balance of the forestry sector, a "drought followed by forest fires" event was introduced at the beginning of the simulation quadrennial 2026-2030. The location and scale of this event could vary according to a "fire risk index," linked to climate conditions. Taking the months of July and August 2003 as a reference point for "current climate," this index predicted a fire risk 2.4 times higher under degraded climate conditions (RCP 8.5). Thus if the total land area burned in a fire event was 75,000 hectares under current climate conditions, the burned area would be estimated to total 175,000 hectares under degraded climate conditions. Tree mortality was assumed to be 100 percent within the burned area.

Compared to the total national forested area, however, this is a relatively small area of impact, corresponding to a small volume of living biomass consumed. Viewed at the national level, the effect of this type of event on the total carbon footprint of the forestry sector remains low (Figures 5 and 6). Total carbon storage in forests, as well as GHG emissions avoided via substitution effects, are unchanged relative to the "no-incident" simulation, even under degraded climate conditions. It should be noted, however, that a series of repeated droughts and forest fires is to be expected, rather than a single episode. The cumulative impact of all these incidents could ultimately make itself felt on the total sector carbon footprint, even if each incident alone has a relatively small effect.

Storms followed by forest fires and/or bark beetle outbreaks

This incident includes a severe winter storm affecting the entire country and causing widespread damage to trees, followed by an outbreak of bark beetles in pines and spruces, followed by forest fires the next summer. Storms Lothar and Martin in 1999, which destroyed 176 Mm^3 of wood in France, were used as reference incidents. The simulated storm would take place in the quadrennial 2026-2030. It would begin in the area of Charente and move across the country from the southwest to the northeast, impacting an area of 700,000 to 1 million hectares.

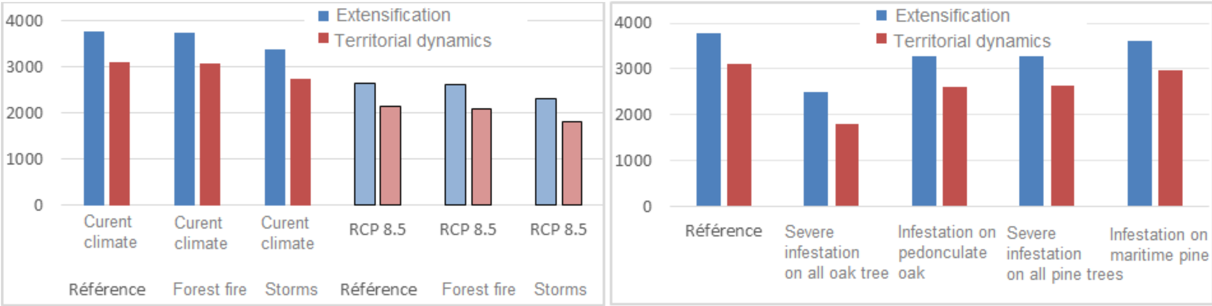

Figure 5: Cumulative C storage in forest ecosystems 2016-2050, two management scenarios with unfavourable events ($MtCO_2$ eq)

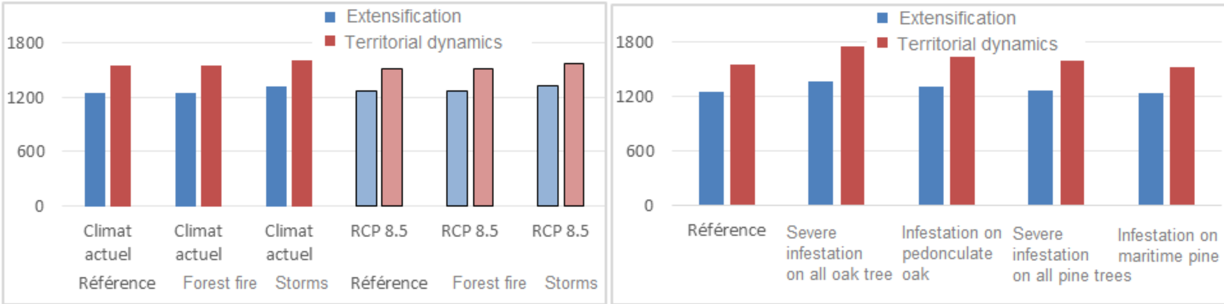

Figure 6: Avoided GHG emissions via substitution effects, cumulative 2016-2050 with unfavourable events ($MtCO_2$ eq)

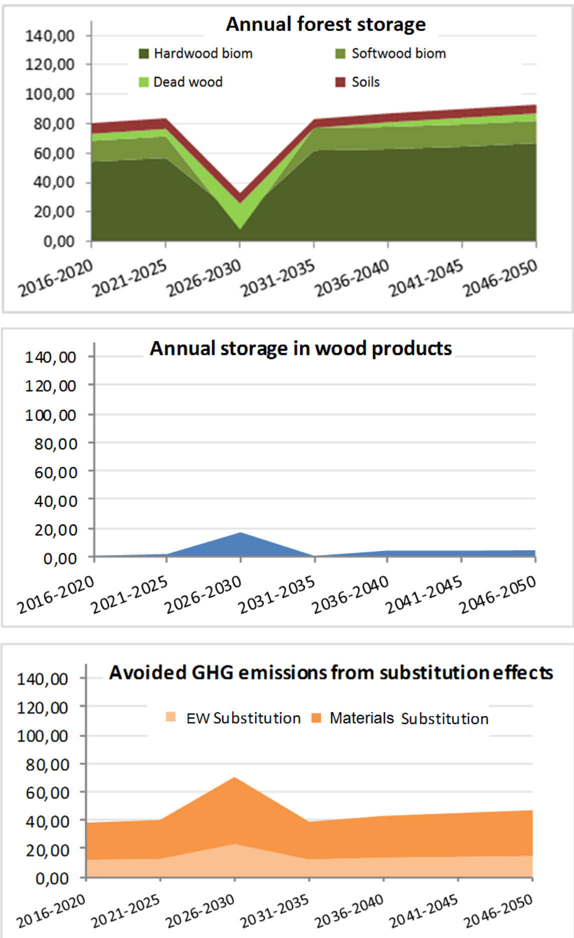

Figure 7: Impacts of a severe storm during the period 2026-2030 on the forestry-sector carbon footprint, followed by bark beetles and fires. Annual C storage and GHG emissions avoided, "territorial dynamics," current climate, $MtCO_2$eq/yr.

In the direct path of the storm, damage to trees exceeds 40%. In addition, in an area totalling 685,000 hectares on the periphery of the storm, tree populations are impacted at levels below 40%.
Although direct damage from the storm is not affected by climate, degraded climate conditions (RCP 8.5) result in additional damage from bark beetle infestations. Tree mortality from bark beetles under current climate conditions reaches 6-12% depending on the tree species and the region; this rate is multipled by 1.7 in the case of a degraded climate (RCP 8.5).

Forest fires the following season are concentrated in the path of the storm. The scale predicted is the same as for forest fires following drought (75,000 ha in the current climate and 175,000 ha in a degraded climate, RCP 8.5). Mortality of remaining trees following the storm is assumed to be total.

Here the effects are much more extensive, at least episodically. Thus, for example, in the case of the "territorial dynamics" scenario, under current climate conditions, annual carbon storage in forests falls dramatically, dropping by 60% from the quadrennial 2021-2025 to the quadrennial 2026-2030, following the storms (Figure 7). The impact on forest biomass is moderated to some extent by the large quantity of deadwood, conserving a portion of the stored carbon in forests. Assuming that large amounts of this wood would be cut and sold, moreover, carbon storage in wood products and the resulting substitution effects would increase in the wake of the storm: avoided GHG emissions would rise sharply, by 75%, and storage in wood products, although still low, would be temporarily multipled by 10.

Overall, the loss of cumulative carbon storage in forests from 2016-2050 due to the combined "storm, bark beetle, fire" incident is greater in the "extensification" scenario than in the "territorial dynamics" scenario (Figure 5). On the other hand, the increase in avoided emissions via substitution effects is slightly more favourable in the "territorial dynamics" scenario than in the "extensification" scenario (Figure 6).

Other pest and disease outbreaks

Finally, we introduced different types of severe pest and disease outbreaks affecting oak and pine species. Parasite spread, mortality dynamics, and loss of growth as determined by the duration of the outbreak were modelled on those seen with ash dieback caused by a fungus. The fungal outbreak results in heavy mortality among young trees, moderate mortality among adult trees, and significant loss of growth. This type of incident was considered independently of other unfavourable circumstances, including climate conditions. It was thus simulated only under "current climate" conditions. The species impacted (oaks or pines) and the severity of the attack determine the scope of the incident. The impact is potentially small if the outbreak is restricted to maritime pine (starting from a localized outbreak in south-western France): in this case, cumulative carbon storage in forests through 2050 would be reduced by less than 5% (Figure 5) and avoided emissions would remain unchanged (Figure 6). The impact would be more substantial in the case of an outbreak affecting pedunculate oaks (*Quercus robur*), given the importance of this species in French forests and an assumed genesis of multiple localized outbreaks in eastern France. A similar impact would be seen if all species of pines were affected.

If, on the other hand, all species of deciduous oaks were susceptible to infection, the impact of an outbreak on the overall carbon footprint of the forestry sector would be major. In this case, annual carbon storage in the biomass of deciduous species would fall significantly from the quadrennial 2021-2025 onward, becoming negative in the two subsequent quadrennials. The increase in stored carbon contained in deadwood would be insufficient to maintain annual carbon storage levels in forest ecosystems and, for the overall period of 2015-2050, total storage would be reduced by a third in the "extensification" scenario and by 42% in the "territorial dynamics" scenario (Figure 5). At the same time, carbon storage in wood products and avoided emissions via substitution effects would increase significantly as a result of the outbreak, but would remain low relative to the loss of carbon storage in forests: +9% for the substitution effect for the full period 2016-2050 in the "extensification" scenario; +12% in the "territorial dynamics" scenario. This is assuming that the timber industry would be able to process 70% of the dying oaks in the "territorial dynamics" scenario, or an annual average volume of 15 Mm^3/yr.

Conclusions and future research needs

The findings of this study suggest that the role of French forestry sector in mitigating climate change is likely to become more significant between now and 2050. Although some components of the sector may show minimal or even negative carbon storage during some periods (for instance, in the wake of a severe storm or pest outbreak), the overall scale of the forest resource makes it a key factor in determining the national inventory of greenhouse gas storage and release. The various compartments and mechanisms considered by this study – i.e., storage in forest ecosystems and in wood products; emissions avoided through substitution effects – play complementary roles in determining the overall carbon balance of the forestry sector. Reductions in carbon storage in living biomass (for example, through intensified timber harvesting, use of short-rotation plantings, or the processing of windfall timber) can be counterbalanced by or made up for over time through avoided emissions resulting from substitution effects, through temporary carbon storage in deadwood, or through more long-term carbon storage in wood products. The benefits to be gained through substitution effects increase with more active forestry management and increased timber harvesting. Stepped up timber harvesting could also generate significant economic and social benefits, but such a shift would require considerable changes in consumer behaviour as well as a some degree of reorganisation of the forestry sector.

Carbon storage in forests is likely to decrease as global temperatures rise and as storms, drought, forest fires, and pest and disease outbreaks increasingly impact forests. Substitution effects, by contrast, are relatively unaffected by these factors. Future scenarios emphasizing more active forestry management thus offer substitution effects that can help compensate for reductions in carbon storage capacity in living biomass.

Given the uncertainty surrounding certain key parameters, it is extremely difficult to rank the three forestry management scenarios presented here in order of their anticipated carbon impacts through 2050. Just as important is the fact that this timeframe falls well short of the length of the typical forestry cycle for hardwood-dominant forests in mainland France. If projections had been attempted for a longer timeframe (through the year 2100 or beyond), the findings of this study might have been different. Modelling tools and methodologies as currently available do not allow for robust simulations over this length of time, however.

Further research is needed to improve methods to measure and assess the carbon balance of the various compartments of the forestry sector, as well as to understand the mechanisms and drivers underlying changes in carbon storage and release as forestry sector strategies, relationships, and conditions change. This study highlights the need for additional data collection, methodological clarification, and multi-disciplinary coordination, particularly with regard to forecasting the future impacts of different climate pathways and associated weather-dependent events. Another key research need is to improve the capacity for integration across different modelling tools: for example, a resource model based on demographic assumptions, a biophysical model with the ability to modify climate conditions, and an economic model allowing analysis of the market factors inhibiting increased timber harvesting. Finally, evaluating the effects of disease and pest outbreaks as linked to biotic and abiotic conditions requires better coordination of data sources, modeling tools, and research on these interactions.

Cover photograph: J.-F. Dhôte

To learn more:

Roux A., Dhôte J.-. (Editors), Achat D., Bastick C., Colin A., Bailly A., Bastien J.-C., Berthelot A., Bréda N., Caurla S., Carnus J.-M., Gardiner B., Jactel H., Leban J.-M., Lobianco A., Loustau D., Meredieu C., Marçais B., Moisy C., Pâques L., Rigolot E., Saint-André L., Schmitt B. (2017). *Quel rôle pour les forêts et la filière forêt-bois françaises dans l'atténuation du changement climatique? Une étude des freins et leviers forestiers à l'horizon 2050*. Study report for the Ministry of Agriculture and Food, INRA and IGN, 96 pp. + 226 pp. of annexes.

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