Economic Evaluation of an Invasive Forest Pathogen at a Large Scale : The Case of Ash Dieback in France

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Economic Evaluation of an Invasive Forest Pathogen at a Large Scale: The Case of Ash Dieback in France

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Abstract
The invasion of a forest by a pathogen is a complex dynamic and spatial problem. The induced disturbances do not only reduce the present availability of the affected tree species but alter its future availability, population structure and distribution as well. These disturbances also have an impact on the prices of wood products via supply shocks, which, in turn, influence forest management choices, thus introducing feedback effects between market and ecological dynamics. The main objective of this paper is to evaluate the economic impact of an invasive pathogen at a large scale by integrating the biophysical and economic aspects of the invasion into a dynamic and spatially explicit setting. The analysis is developed using a modified version of the French Forest Sector Model (FFSM), a recursive partial equilibrium model, to which a specifically designed pathogen spread and mortality model have been coupled. We calibrated the model to represent the ash dieback invasion in France. Results showed that impacts are not homogeneous across regions and generally depend on the resource distribution, pathogen spread and market structure. We observed that the behavioural adaptation of forest managers (i.e. regeneration and harvesting choices) is a non-negligible component of the total standing volume loss.

Keywords Invasive species · Forest economics · Economic evaluation · *Hymenoscyphus fraxineus* · Ash dieback · Recursive partial equilibrium model

1 Introduction

The evaluation of the economic impacts of an invasive pest or pathogen is a challenging exercise. Pest and pathogen invasions do not only reduce the current availability of the affected species but will also alter its future availability as well as change the whole structure of invaded forests both in terms of species composition and age distribution. In addition to these ecological dynamics, the markets for timber and wood-based products will also be affected by the invasion. The shocks in resource availability will probably change the present and future market prices and, eventually, consumption and production choices. Feedback effects between the economic and the ecological dimensions may play an important role. For example, if the attacked species is expected to face high pathogen-related mortality in the future, forest managers might prefer to select other species when making regeneration choices. This will even further reduce the presence of the attacked species in the landscape. Finally, pathogen invasion is not only a dynamic problem but a spatial problem as well. Pest or pathogen spread and the availability of control methods will probably have major welfare impacts, at least in the short run, across invaded and non-invaded areas.

As pointed out by Holmes [1], the economic evaluation of pest and pathogen invasions at a large scale has generally been achieved using accounting data, multiplying a unit price observed in the timber markets by a physical quantity (volume losses). However, this accounting approach [e.g. 2–4] is not consistent with microeconomic theory since it neglects the fact that biological invasions are dynamic processes to which the forest ecosystem, forest managers, and markets react.

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Recent studies addressed the problem of biological invasions in a more sophisticated manner by integrating the quantification of economic impacts with spatially explicit models able to capture the spread and dynamics of a biological invasion in different ecosystems [5–7]. This approach has been applied to forest ecosystems, focusing on estimating the total damages and costs of invasion [8–10] or the benefit from exclusion [11], as well as assessing spread control programmes [12].

Although these studies are able to represent large-scale spread and forest and pest dynamics, as well as the quantification of biophysical and harvest-related economic impacts [6], they are unable to capture the behavioural responses made by producers and consumers in the forest sector since economic conditions adjust to changes in forest health. In order to account for the behavioural response of economic agents to changes in forest health conditions, Holmes [13] proposed using a forest sector market model to account for prices and welfare changes. Holmes focussed on established pest outbreaks, and Soliman et al. [14] extended this approach to pest and pathogen invasion with an advancing front by combining a partial equilibrium model to a spatially explicit pathogen spread and pathogen-induced mortality models.

The main objective of this paper is to evaluate the economic impacts of an invasive pathogen at a large scale by capturing not only the biophysical damages but also their impacts on the forest product market equilibria. In particular, we are interested in identifying the direct impact of pathogen mortality, as well as the feedbacks and adaptation effects. We add to the work of Soliman et al. [14], who focussed on one single market only, by using a recursive partial equilibrium model of the entire forest sector. Moreover, our analysis integrates a multi-species forest growth model linked to a spatially explicit endogenous management model (i.e. the harvesting and regeneration choices depend on present market prices and expected future revenues). In this way, it is possible to capture the behavioural response of rational, forward-looking forest landowners to the biological invasion. We applied this method to the invasion of ash dieback in France. We used the French Forest Sector Model (FFSM), an integrated bio-economic tool [15, 16], coupled with spatially explicit pathogen spread and mortality models.

To our knowledge, only one study has attempted to quantify the economic costs and damages of ash dieback in a European country [17]. In his work, Worrell attempted to define the overall impact of ash dieback invasion in Scotland, where ash represents about 8% of the broadleaf standing volume. The author accounted for the potential costs for woodland owners (e.g. the costs of complying with forest health regulations, monitoring costs and the costs of replacing ash with alternative species) and the impacts on timber markets as well as on ecosystem services provision. However, given the scarcity of data on ash (hardwoods other than beech are usually combined in forest statistics) [18] , the quantitative assessments presented in Worrell's work are often computed via rough estimates of the market conditions as well as of resource availability. The dynamic aspect of the problem and the possible future impacts are generally qualitative and based on experts' opinions.

Our work also aims to contribute to the quantification of the economic impacts of ash dieback by addressing the problem dynamically and consistently with microeconomic theory. To do this, we tested five different scenarios according to the level of substitutability between ash products and other hardwood products and the nature of forest managers' expectations regarding pathogen spread.

2 Problem Context: Ash Dieback in Europe and France

Common ash (*Fraxinus excelsior*) is a major tree species in Europe. From an ecological point of view, it is considered as a keystone species, particularly in riparian forests [18]. From an economic viewpoint, ash timber is in great demand because of its pale colour and its physical properties (elasticity, hardness and resistance to pressure). It is used for the production of many products such as furniture, veneer and flooring [19].

Ash plays a relevant socio-cultural role in many parts of Europe in terms of landscape. As a pioneer species, ash also plays an important role in both primary and secondary successions, making it possible for shade-tolerant species such as beech to establish themselves [20]. In France, common ash is the fifth major broadleaf species, both in terms of volume and area, after oak, beech, chestnut and hornbeam; 4% of the forest area in France is covered by common ash [21].

Ash dieback was first observed in Poland at the beginning of the 1990s, but the cause was initially not identified. Later, in 2006, it was discovered that ash dieback was caused by the new anamorphic species of fungus, *Chalara fraxinea* [22]. In 2011, the sexual stage of the fungus was described as *Hymenoscyphus pseudoalbidus* [23], then renamed as *Hymenoscyphus fraxineus* [24]. This pathogen has roots in Asia, although the circumstances of its introduction into Europe are still unclear [25].

At present, *Hymenoscyphus fraxineus* has spread across the European continent as well as the UK, with the exception of southern France, southern Italy and the Iberian Peninsula [18]. In 2008, the first cases of ash dieback were reported in north-eastern France. Since then, the infection front has advanced rapidly. The disease generally spreads through airborne spores produced from fruiting bodies on leaf litter and leaf infections. Long-distance dispersal can be

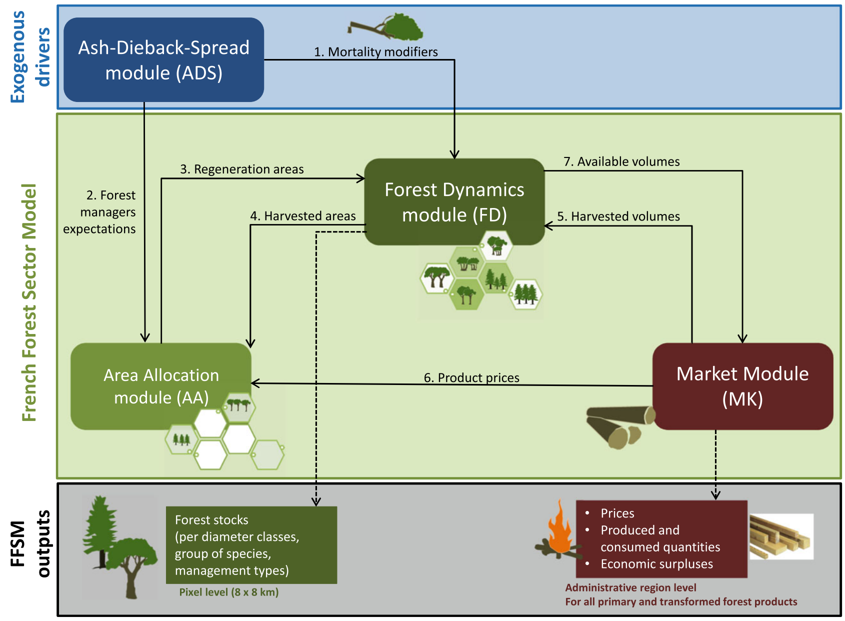


Fig. 1 Overall structure of the modelling framework used

also human mediated through the transportation of infected planting material from nurseries.

The pathogen causes lesions on leaves, canker on twigs and shoots, xylem decay and collar canker in older trees. The disease affects trees in all age classes. The mortality rate on ash trees of all ages is high after several years of infection, although death occurs more quickly in young plants [26]. So far, there are no effective large-scale management protocols for the mitigation of damage caused by ash dieback. Current management recommendations suggest keeping tolerant ash trees in the forest to provide reproductive material.

3 Methodology

3.1 The French Forest Sector Model

Overall structure FFSM is an integrated model of the French forest system that explicitly accounts for forest biological dynamics, management decisions and wood markets. FFSM is composed of three interconnected modules [15, 16]: the inventory-based Forest Dynamics (FD) module, the partial equilibrium Market (MK) module and the micro-based Area-Allocation (AA) module. Figure 1 illustrates the modelling framework and the connections between the modules. Solid arrows refer to transfers of information from one module to the other while dotted lines represent FFSM outputs. Differently from previous studies using FFSM, in this work we included a fourth module, namely the Ash-Dieback-Spread (ADS) module. The ADS module exogenously affects forest system dynamics in two ways: (i) by increasing the forest mortality (see arrow n.1 in Fig. 1) and ultimately affecting the Forest-Dynamics module; (ii) by modifying forest managers' expectations on future forest revenues (see arrow n. 2 in Fig. 1) and eventually influencing the Area-Allocation module.

FD Module The FD module is based on an 8 × 8 km grid. Using the data from the French National Forest Inventory (FNFI), the FD module was built to account for the total tree volume for each cell and its distribution across four combinations of forest covers and structures, referred from now on as "forest types": *broadleaf high forest*, *broadleaf high forest and coppice*, *broadleaf coppice* and *conifers*. In the FD module, the total volume in each cell (for each forest type) was distributed across 13 diameter classes using the data from the FNFI. For each forest type and each diameter class, biological dynamics stem from growth and mortality rates computed using data from the 2005–2007 FNFI.

To analyse the impacts of ash dieback, we modified the FD module by adding a new specific forest type to account for ash tree population. We estimated the ash volume distribution in each cell (Fig. 2) using geostatistical techniques [27, 28]. Data on ash populations was taken from the FNFI carried out by the French National Institute of Geographic and Forest Information (IGN) for the years 2006–2010 [29].[1] For ash volume dynamics, we used the same age class growth model (including natural mortality not related to ash dieback), which was originally calibrated for the broadleaf species.

The sum of the total ash volume in France obtained from our estimations is 103.48 million m^3 for the year

[1]See the Appendix A for details on the ash volume estimation and distribution in diameter classes.

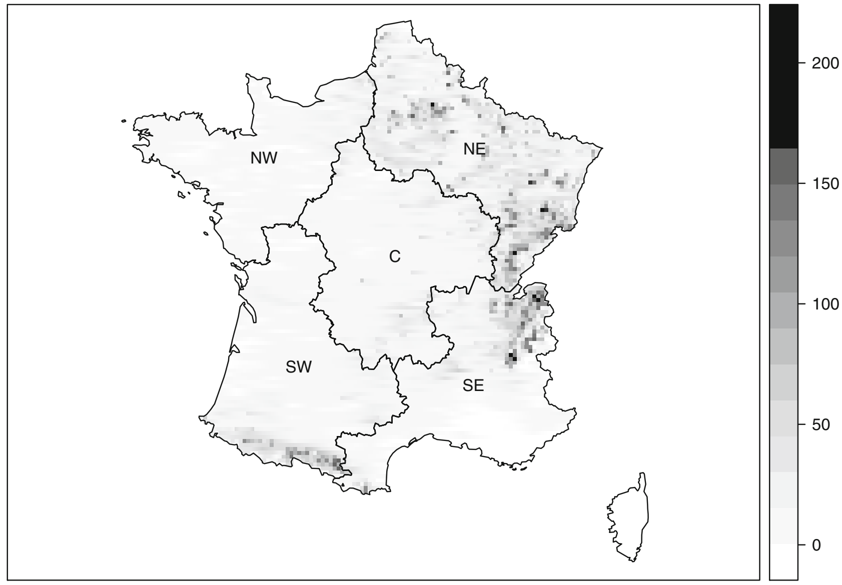


Fig. 2 Estimated ash standing volume distribution in 2010 (cubic metres per hectare)

2010 (Table 1), which is rather close to the 103 million m^3 reported by the FNFI [29]. We also compared the ash volume estimations with the inventory data at the regional level. Besides for two regions in which the model overestimated the total ash volume (Lorraine and Rhône-Alpes) and one region for which it was underestimated (Champagne-Ardenne), the estimations were fairly close to the observed data and the error was lower than the 95% confidence interval reported by the FNFI results (Table 1, last two columns).

In order to simplify the illustration of the results, we grouped the 20 French regions into five macroregions, trying to be as close as possible to the map of the French ecological regions while maintaining a simple layout. In Table 1 and Fig. 2, it is possible to see the composition of the five macroregions: Northeast, Northwest, Centre, Southeast and Southwest.

MK Module The MK module consists of a partial-equilibrium model representing the French forest sector from timber production to the consumption of first-transformation products [30]. In its original form, the model accounted for three raw timber products, denoted by w (i.e. industrial wood, hardwood and softwood roundwood) and six processed timber products, p (i.e. hardwood sawnwood, softwood sawnwood, plywood, pulp, fuelwood, and fibre and particle board). We modified the original FFSM market module to account for ash wood products: we allowed the model to account for a new primary product, namely ash roundwood, distinct from hardwood roundwood. Ash roundwood can be transformed into ash sawnwood and ash plywood as illustrated on Fig. 3. Given the lack of data on the ash wood market—specifically, on the cross-elasticity of substitution between ash and other hardwood products—we

Table 1 Comparison between the estimated total ash volume and the total ash volume from the French National Forest Inventory (FNFI—million cubic metres, 2010)

Region	Estimated	FNFI	95% C.I. (±)	Error
Northeast:				
Alsace	3.73	4	1	– 0.27
Champagne-Ardenne	8.51	12	1	– 3.49
Franche-Comté	11.76	11	2	0.76
Île de France	4.12	4	1	0.12
Lorraine	9.63	8	2	1.63
Nord-Pas de Calais	2.59	2	1	0.59
Picardie	7.98	8	1	– 0.02
Northwest:				
Basse-Normandie	1.23	1	1	0.23
Bretagne	0.71	1	1	– 0.29
Haute-Normandie	2.49	2	1	0.49
Pays de Loire	1.00	2	1	– 1.00
Centre:				
Auvergne	4.26	5	1	– 0.74
Bourgogne	5.42	5	2	0.42
Centre	2.81	3	1	– 0.19
Limousin	1.03	1	1	0.03
Southeast:				
Languedoc Roussillon	2.29	2	1	0.29
Provence-Alpes-Côte d'Azur	0.99	1	1	– 0.01
Rhône-Alpes	17.77	15	1	2.77
Southwest:				
Aquitaine	3.96	4	1	– 0.04
Midi-Pyrénées	9.72	10	1	– 0.28
Poitou-Charentes	1.49	2	1	– 0.51
France (total)	103	103	6	

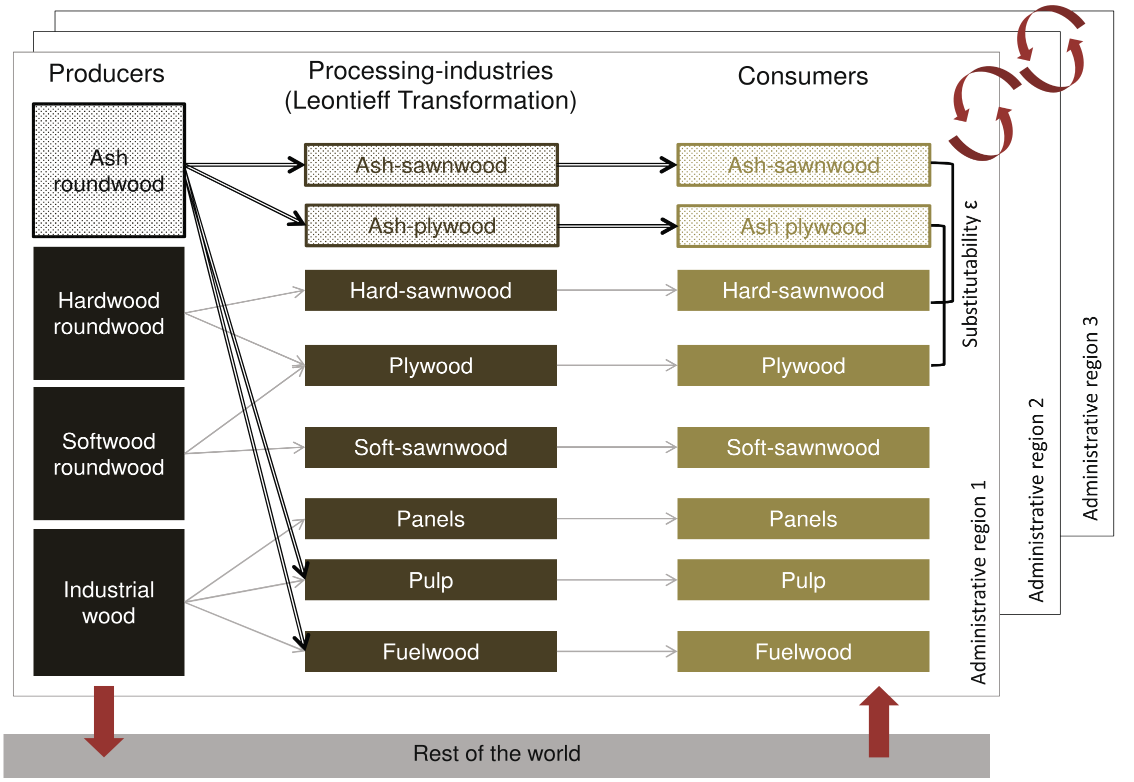


Fig. 3 FFSM initial market module and inclusion of the ash wood sector

decided to test different scenarios representing alternative market structures (see Section 3.2).

Three groups of agents are represented in the model: wood suppliers, the transformation industry and consumers (either final consumers or second-transformation industries). Each year, the resource availability computed in the FD module is used in the MK module to determine the supply curve through a positive elasticity of the supply to the resource that remains constant in the model. Each product has its own forest type and diameter class range that count as "available resources", e.g. fuelwood can be produced from lower diameter classes than sawnwood.

The MK module solves, for each of the 22 French administrative region, a partial equilibrium problem according to Samuelson [31] spatial price equilibrium framework. To do so, it annually computes (1) the optimal demand of processed products p and (2) the optimal supply of raw products w, (3) the optimal prices associated to these quantities and (4) the amount of wood products w and p traded between regions and with the rest of the world (i.e. imports and exports). A Leontief function represents the transformation of raw products into processed products. This equilibrium explicitly accounts for wood availabilities in the forest, for the costs of transformation in processing industries and for the costs of transportation from one region to another following the Samuelson theory [31]. In addition, supply and demand functions are built assuming the Armington framework [32], i.e. domestic and foreign forest product consumption and production are considered to be imperfectly substitutable [33].[2]

The regional supply S of primary forest products w in region i takes the form of Eq. 1, where $P_{w,i}(t)$ is the regional price of the primary product at time t, ϵ_w is the elasticity of supply to price and β_w is the elasticity of supply to available resources in forest. Both elasticities are derived from Buongiorno et al. [34] and are kept as constant over the simulation horizon.

$$S_{w,i}(t) = S_{w,i}(t-1)\left(\frac{P_{w,i}(t)}{P_{w,i}(t-1)}\right)^{\epsilon_w}\left(\frac{F_{w,i}(t)}{F_{w,i}(t-1)}\right)^{\beta_w} \tag{1}$$

Likewise, in each region i, the demand curves D of processed products p use exogenous elasticities σ_p of demand to price calibrated by Buongiorno et al. [34] for high-income countries.

$$D_{p,i}(t) = D_{p,i}(t-1)\left(\frac{P_{p,i}(t)}{P_{p,i}(t-1)}\right)^{\sigma_p} \tag{2}$$

Once the optimal wood supply level has been computed, it is transferred to the FD module to be subtracted from

[2]The assumption of imperfect substitutability between domestic and foreign products is justified by product heterogeneities that depend from production places, by the consumers habits or by the market structure [33].

the current standing wood volume. In addition, equilibrium prices are transferred to the AA module in order to model forest managers' replanting decisions.

With the market equilibrium determined in terms of quantities and prices, the MK module allows performing welfare analysis, i.e. to compute the total welfare of the economic agents as the sum of the consumer surplus and the producer surplus.[3]

AA Module The AA module is responsible for reallocating the harvested forest area to a specific forest type. Differently from the harvesting decision, which is regulated by the MK module partially as a function of conjunctural timber prices, we model this choice as a long-term investment decision in which the expected profits from the available investment options (i.e. the forest types) are compared. The AA module is hence an agent-based model where individual forest managers are modelled as profit-maximising economic agents that are heterogeneous in terms of the degree of risk-aversion (the level of expected profit that they are willing to trade in exchange for a lower uncertainty over future forest profitability) and level of expectations (ranging from myopic behaviour that considers only observed information to perfect foresight behaviour that accounts for future changes). In other terms, each individual forest manager m is characterised by a risk aversion coefficient α_m and expectation level β_m that are randomly sampled from scenario-specific distributions.

Given the set of forest investment alternatives, forest manager m selects the forest investment option j if and only if it offers the largest expected profit, denoted by $\pi_{j,m}$. Expected profits are expressed in terms of risk-free Equivalent Annual Income (EAI) computed from marketing the harvested logs and depend from (1) forest managers characteristics, i.e. the risk aversion coefficient α_m and expectation level β_m; (2) forest investment j's characteristics, i.e. the vectors of the expected growth $\boldsymbol{g}_j$ and mortality $\boldsymbol{\omega}_j$ rates for each period until the end of the rotation; and (3) transaction cost proportional to the proximity between investment j and the previous rotation investment, denoted by k, in order to account for knowledge and machinery gaps and more generally frictional costs related to changing species or management regime. Formally, the forest managers' investment decisions are expressed as:

$$\max_j(\pi_{j,m}) = \pi_{j,m}\{\alpha_m, \beta_m, \boldsymbol{g}_j, \boldsymbol{\omega}_j; c_{j,k}\}. \quad (3)$$

We refer to Lobianco et al. [15] for the description of the functional forms used for the expected profits. Here, it is important to highlight how a sudden tree mortality surge, as those induced by the ash dieback, influences the expected profits in the model. First, a mortality outbreak, at constant harvested volumes, expands the area available for new regeneration. This is a consequence of the fact that, in our model, trees that die before reaching maturity are not removed from the stand but become unsuitable for commercial uses (this to capture the effect of potential secondary infections from other pathogens). Hence, mortality reduces the per-hectare marketable volumes and the expected returns. The amount of this reduction depends on the mortality level, but also on the forest managers' expectations: perfect foresight managers (with $\beta_m = 1$) will fully anticipate the reduction of the timber quantity at maturity caused by ash dieback, whereas myopic agents ($\beta_m = 0$) will start to account for it only when the pathogen is present in their forest. Managers with $0 < \beta_m < 1$ form their expectations midway.

The last way in which ash dieback influences the expected returns is through the rise in risk. Given that we defined risk as the average total mortality across the rotation for each forest investment option j, an increase in the mortality, along with reducing the average expected profits, decreases the risk-free equivalent profit, by an amount proportional to the individual α_m coefficient. Conversely, as timber prices are endogenous to the model (that is recursive, i.e. it runs year after year), market effects associated with the ash dieback are not anticipated by forest managers, as the only anticipation in timber prices concerns exogenous changes in world prices.

The AA module recognises that not all forest investment decisions are profit oriented, so we leave a quota of forest area where regeneration follows alternative drivers. In this paper, we set this quota to 30% with an alternative driver that simulates a more ecological approach where the regenerated forest option i is the same as the previous rotation one in order to approximate the effect of natural regeneration. The regeneration area is then used to compute the new regeneration volumes in the FD module.

ADS Module The pathogen spread was modelled as a radial range expansion model, which is a simplified version of the reaction diffusion model [35]. We opted for a simpler diffusion model because of the lack of information available regarding the relationship between the pathogen spread and the host population distribution. Nonetheless, the model can be easily adapted to account for more complex pathogen spread dynamics, for example Ecological Niche Models with explicit consideration for present and future environmental conditions [36]. We set the annual average disease progression rate to 50 km per year, as found in previous works on the French invasion [37, 38].[4] We used

[3]The consumer surplus is the difference between what consumers are willing to pay for a given good and the actual market price. The producer surplus is the difference between the price at which producers are willing to supply that good and the actual market price.

[4]Other studies report a disease progression rate in Europe (or in European countries) between 40-75 km per year [25, 39, 40], which is in line with the values indicated for France.

the locations where the pathogen was initially detected in 2008 in the north-western part of France as entry points. We also included the second introduction point in northern France in 2010 (Fig. 4a).

Concerning the pathogen-induced mortality, a recent study suggested the link between ash dieback and the intensity of the girdling necrosis at the collar [41]. The intensity of the collar necrosis seems to depend both on the number of years since the infection and the tree size. Based on this study, the pathogen-related mortality rate was modelled as a function of the years since the infection. Three different mortality functions were defined (Fig. 4b): one for the seedlings (diameter less than 5 cm); one for young trees (diameter between 5 and 25 cm); and one for older trees (diameter greater than 25 cm).

3.2 The Scenarios

One of the most important hypotheses of the model is the degree of substitutability between ash products and other hardwood products for the consumer. Unfortunately, it was not possible to obtain the data necessary to estimate these elasticities of substitution, and therefore, we tested different cases. We modelled the FFSM market module to integrate the demand for ash products in two different ways, depending on the level of substitutability between ash and other hardwood products.

On the one hand, we considered the situation in which ash wood is perceived as any other hardwood, i.e. consumers are not able to discern ash products from other hardwood products. Therefore, harvested ash wood is used together with the wood of other broadleaf species to produce undifferentiated hardwood roundwood that is then transformed into secondary hardwood products. We referred to this scenario as "*perfect substitutability*", indicating that ash and other hardwood products are similar in every respect. Consequently, we keep the generic demand function defined in FFSM:

$$D_{h,i}(t) = D_{h,i}(t-1)\left(\frac{P_{h,i}(t)}{P_{h,i}(t-1)}\right)^{\sigma_h} \tag{4}$$

where:

- $D_{h,i}(t)$ is the demand for an undifferentiated hardwood product (e.g. hardwood plywood, hardwood sawnwood, etc.) indicated by $h = 1, \ldots, H$, in region i at year t;
- $P_{h,i}(t)$ is the price of an undifferentiated hardwood product h in region i at year t;
- σ_h is the price elasticity of the demand for an undifferentiated hardwood product h.

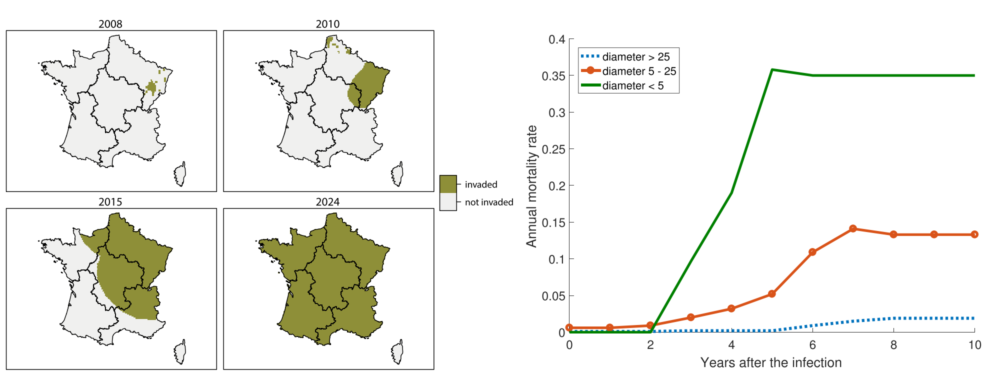
In this case, the original FFSM market module was not modified, with the exception of the inclusion of ash wood as an input to produce hardwood products. $D_{h,i}(t)$ then represents hardwood products made of broadleaf species, including common ash.

On the other hand, we tested a different market setting in which ash wood is used to create a specific primary good, "ash roundwood", which is transformed into two secondary products: "ash plywood" and "ash sawnwood". In this second case, the FFSM market module was modified to account for these new ash-specific products. As in the case for the other products in the model, each ash product has its own market and demand that depends on the current price as well as on the price and the demand in the previous period. However, unlike the other hardwood and softwood products, the demand for a specific ash product also depends on the price of its substitute product (i.e. the demand for "ash sawnwood" depends on the price of "other hardwood sawnwood"). Specifically, the demand of a specific ash product (e.g. ash plywood, ash sawnwood), denoted by $a = 1, \ldots, A$, is:

$$D_{a,i}(t) = D_{a,i}(t-1)\left(\frac{P_{a,i}(t)}{P_{a,i}(t-1)}\right)^{\sigma_a} \underbrace{\left(\frac{\left(\frac{P_{a,i}(t)}{P_{b,i}(t)}\right)}{\left(\frac{P_{a,i}(t-1)}{P_{b,i}(t-1)}\right)}\right)^{\epsilon_{a,b}}}_{\text{Competition module}} \tag{5}$$

where:

- $D_{a,i}(t)$ is the demand for an ash product in region i at year t;



(a) Spread moddel

(b) Mortality function

Fig. 4 Ash dieback spread model and mortality functions for ash seedlings (diameter < 25 cm), young ash trees (diameter 5–25 cm) and older ash trees (diameter > 25 cm)

- $P_{a,i}(t)$ is the price of an ash product in region i at year t;
- $P_{b,i}(t)$ is the price of the other hardwood substitute b in region i at year t;
- $\epsilon_{a,b}$ is the cross-elasticity of demand between ash and the other hardwood substitute;
- σ_a is the price elasticity of the demand for an ash product.

Equation 5 allows to modulate the degree of substitutability between a product made of ash and a hardwood substitute.

This modelling choice is supported by the fact that the ash product market is a niche market because of the low volume produced (the ash trees harvested represents about 2.6% of the total annual harvested volume, average 2007–2015). Therefore, it is reasonable to imagine that the demand for ash products is also affected by the price of their respective substitutes.

In this setting that is characterised by ash-specific markets, we assumed two scenarios. Firstly, we created a scenario in which the degree of substitutability of ash products and other hardwood products is rather low. In this case, we implicitly assume that consumers strongly prefer ash products over other hardwood products. Hence, when the price of an ash product increases abruptly and the price of other hardwood products remains stable, the ash product demand decreases only marginally. In other words, for the consumers, ash products are rather unique and difficult to substitute with other hardwood products. We referred to this scenario as "low substitutability" and assumed that $\epsilon_{a,b} = -0.001$.

Secondly, we tested an intermediate scenario in which ash and other hardwood products are substitutable. This scenario is referred to as "intermediate substitutability", and we tested the following alternative values of $\epsilon_{a,b}$: -0.01, -0.1, -0.5, -1, -2.5, -5. To simplify the illustration of the results, we present results only for $\sigma = -1$. However, all of the simulation results are available in the supplementary material (see Supplementary Materials).

Another important aspect in a dynamic model is the way decision-makers form their expectations. For this reason, we tested three alternative representations for expectations. The first setting assumed full foresight concerning the spread of the pathogen. Under this assumption, forest managers account for the additional mortality induced by the pathogen and the effect that this will have on the availability of timber when ash trees are ready for harvesting when they plan for new forest investments. Second, we introduced an alternative setting in which forest managers are myopic and assume that the observed ash dieback mortality at the time of making the investment decision will remain unchanged for the future periods. Third, we tested an intermediate setting with partial information about the spread. In this case, "awareness" about future pathogen spread increases progressively as the first symptoms appear, and different forest managers are allowed to take different positions, in between the two extremes. We referred to these expectation hypotheses as "perfect foresight" ($\beta_m = 1$), "myopic" ($\beta_m = 0$) and "intermediate foresight" ($0 < \beta_m < 1$), respectively.

We used the "intermediate foresight" expectation hypothesis as the baseline case, and then tested the sensitivity of the model on this assumption for the "intermediate substitutability" market scenario. A summary of the scenarios tested is presented in Table 2. We ran each scenario with and without the pathogen presence for a planning horizon ranging from 2008 to 2060.

4 Results

In this section, we present the results of the simulation for the horizon 2008–2060, first focusing on the resource impacts, then on the market impacts and, finally, on welfare changes. We will mainly discuss the results for the scenario "intermediate substitutability" (IS-IF), with a unit cross-elasticity between ash and other hardwood products and intermediate foresight on the future spread. Results are presented for the alternative scenarios when significant differences are observed.

4.1 Resource Impacts

The overall trend of the French forest sector in the absence of major shocks, i.e. without accounting for ash dieback or other catastrophic events, reveals a robust increase of the standing volume, in particular for broadleaf species. This is the result of the present under-harvesting of the resource.

Table 2 The simulated scenarios

Code	Scenario name	Market setting	Expectation setting
IS-IF	Intermediate substitutability	Eq. 5, $\epsilon_{a,b} = -1$	Intermed. foresight
LS-IF	Low substitutability	Eq. 5, $\epsilon_{a,b} = -0.001$	Intermed. foresight
PS-IF	Perfect substitutability	Eq. 4	Intermed. foresight
IS-MF	Myopic foresight	Eq. 5, $\epsilon_{a,b} = -1$	Myopic foresight
IS-PF	Perfect foresight	Eq. 5, $\epsilon_{a,b} = -1$	Perfect foresight

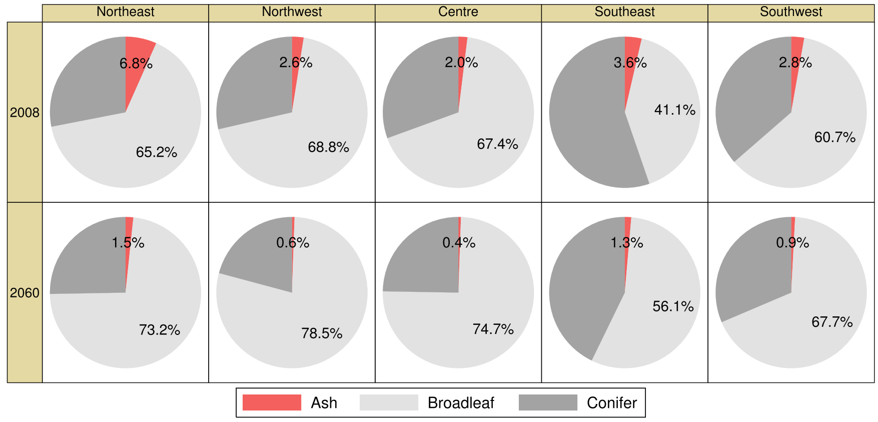


Fig. 5 Standing volume distribution across forest types for years 2008 and 2060 in the "intermediate substitutability" scenario (IS-IF) with ash dieback

Therefore, in the absence of the ash dieback invasion, our simulations suggest that common ash would follow the same pattern of the other broadleaf species, increasing its standing volume by about 160% and reaching 260 million m^3 by 2060.

When we account for pathogen invasion and spread, we forecast that ash dieback will be present throughout the entire France territory, with the exception of Corsica, by 2024 (Fig. 4a). According to the mortality rate registered until now, our projections show that, with ash dieback, the ash standing volume will be 70 million m^3 less in 2030 compared to the case without ash dieback. At the end of the planning horizon, according to the current mortality rate and lack of control mechanisms, this difference will be in the range of 200 million m^3. Hence, 78% of the potential standing volume will be lost by 2060. The percentage of ash standing volume is decreasing in all regions in favour of other tree species, with the Northeast macroregion the most affected (Fig. 5). In general, in 2060, ash is predicted to be about 1% of the total standing volume in all macroregions. Overall, the standing volume variations are quite robust across the simulated scenarios (Table 3).

As a result of the drop in the ash standing volume, the ash harvested volume is also reduced by the pathogen presence. By summing up all the annual harvest losses[5] over the entire planning horizon 2008–2060, the cumulated contraction in the harvested ash volume is predicted to be 37 million m^3 (Table 4, last row).[6] When "perfect substitutability" is assumed (scenario PS-IF), the cumulated reduction in the harvested volume is higher and reaches 42 million m^3. In this case, other broadleaf trees will be harvested more intensively to partially compensate for the reduction in supply caused by the pathogen presence (Table 4).

Another important aspect to consider is the adaptive behaviour of forest managers to the ash dieback invasion. After a final cut, the forest manager has to decide how to regenerate the forest land. He/she is free to keep the previous forest type or change it for an alternative one. This decision depends on the future revenues that the forest owners expect to receive from the different forest types. In Fig. 6, we present the expected revenues computed in three reference years: 2008, when the invasion started; 2015, when the invasion is half way through; and 2030. By comparing the expected revenues with and without the pathogen, it is possible to observe that the decline is rather sharp just seven years after the invasion. In 2015, the expected revenues from ash remain unaffected only in the not-yet-invaded southern part of France. In 2030, the expected revenues from ash are very close to zero in all macroregions. The expected revenues from other broadleaf species and conifers are, in contrast, unaffected by the invasion. We tested the sensitivity of the expected revenues on the forest managers' expectations. The reduction of the expected revenues caused by ash dieback is rather similar

Table 3 Ash standing volume losses across different scenarios using the case without ash dieback as the baseline (M m^3—percentage changes in brackets)

Year	IS-IF	LS-IF	PS-IF	IS-MF	IS-PF
2015	3.85	3.85	3.84	3.85	3.85
	(3.2)	(3.2)	(3.2)	(3.2)	(3.2)
2030	70.59	70.61	69.66	70.64	71.22
	(42.1)	(42.1)	(41.8)	(41.9)	(42.0)
2045	140.71	140.81	137.36	140.16	143.31
	(65.2)	(65.2)	(64.2)	(64.9)	(65.3)
2060	201.80	201.99	195.41	199.87	207.07
	(78.4)	(78.4)	(76.7)	(78.0)	(78.5)

[5]The annual harvested loss is the difference between the harvested ash volume without ash dieback and the harvested ash volume with ash dieback in a specific year.

[6]The reduction in the ash harvested volume is robust for the tested values of the cross-elasticity of substitution between ash products and other hardwood species, i.e. $\epsilon_{a,b}$: −0.01, −0.1, −0.5, −1, −2.5, -5 (results not reported in the text, but available upon request).

Table 4 Comparison of the cumulated changes in the harvested volume of ash, other broadleaves and conifers for the "intermediate substitutability" (IS-IF) and "perfect substitutability" (PS-IF) scenarios, expressed in million cubic metres, for the simulated period 2008-2060

	Ash		Other broadleaves		Conifers	
	IS-IF	PS-IF	IS-IF	PS-IF	IS-IF	PS-IF
Northeast	– 24.59	– 28.19	11.38	14.76	3.52	3.33
Northwest	– 2.82	– 3.15	1.41	1.84	0.32	0.31
Centre	– 3.98	– 4.39	3.87	4.96	1.08	1.10
Southeast	– 2.76	– 3.20	1.08	1.54	0.97	0.96
Southwest	– 2.97	– 3.25	2.88	3.29	1.91	1.90
France (total)	– 37.11	– 42.18	20.63	26.39	7.79	7.59

in terms of percentage. However, in absolute terms, in the scenario with perfect foresight (IS-PF) the reduction is larger than in the intermediate foresight case (IS-IF). Similarly, when we assume a myopic foresight (IS-MF), the difference in the expected revenues with and without pathogen spread is lower. In other words, the myopic forest managers are not able to anticipate the future increase in ash mortality and they therefore overestimate the expected revenues. The same can be said, although to a lesser extent, for the intermediate scenario. This is then reflected in the regenerated area. Myopic forest managers will reduce the area regenerated with ash in favour of other forest types at a much lower rate than forest managers with perfect foresight.

The total reduction of the standing volume (Table 4) can then be explained by the direct effect of the pathogen mortality and the forest managers' replanting choices. In Table 5, we now isolate these two effects – *pathogen mortality* and *adaptation* – revealing their individual contribution to the total volume reduction. We first quantify *pathogen mortality* by simulating the scenarios, keeping the share of each forest type constant over time and equal to the one present in the initial period. In other words, the forest manager cannot change the species portfolio after the harvest. We then compute the *adaptation* as a residual between the total volume reduction and the *pathogen mortality*. In the "intermediate substitutability" scenario (IS-IF), the *pathogen mortality* effect is the main driver of the reduction in ash standing volume, accounting, on average, for 94% of the total volume losses. *Adaptation* is nonetheless non-negligible and accounts for 6% of the total volume losses between 2008 and 2060. The *adaptation* effect ranges from 4.1% in the "myopic foresight" scenario (IS-MF) to 7.4% in the "perfect foresight" scenario (IS-PF). Furthermore, the composition of the total volume losses between the two effects varies across the five macroregions. In particular, the *adaptation* effect is larger in the northern macroregions compared to the southern ones. Although several factors are likely to play a role, we think that this spatial differentiation may be explained by the fact that in the northern macroregions, ash is generally a competitive choice for

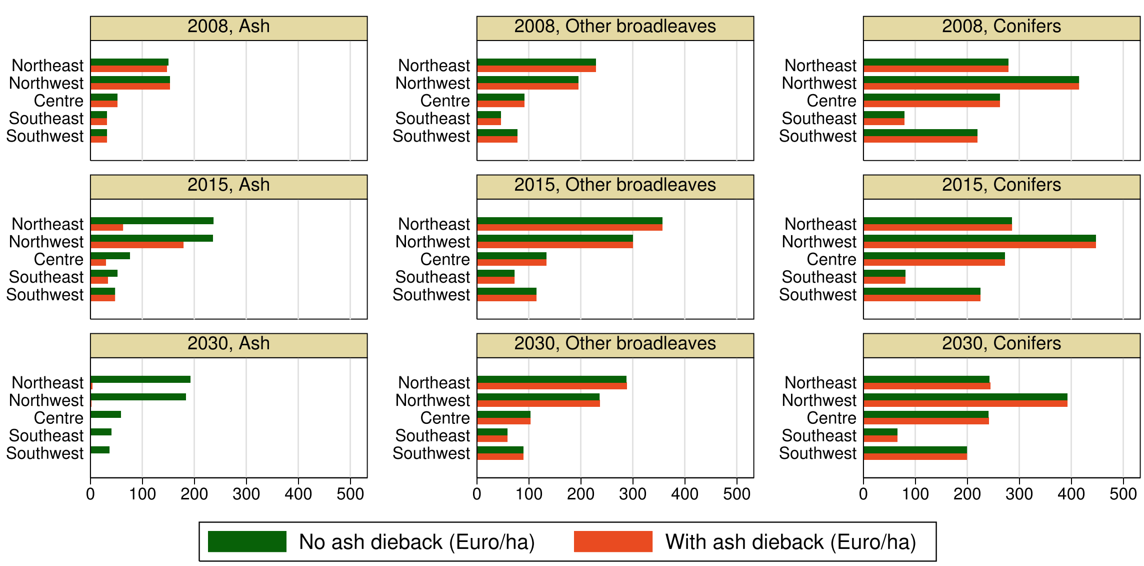


Fig. 6 Comparison of the expected returns for different forest types in 2008 (above), 2015 (middle) and 2030 (below) for the scenario IS-IF, with and without ash dieback. The data are presented for each macroregion

Table 5 Total volume reduction divided into *pathogen mortality* and *adaptation* effect for the "intermediate substitutability" scenario (IS-IF)

		Effects	
	Total volume loss (M m^3)	Pathogen mortality (%)	Adaptation (%)
Northeast	94.06	91.2	8.8
Northwest	9.03	90.9	9.1
Centre	26.94	97.5	2.5
Southeast	44.21	96.4	3.6
Southwest	27.57	97.4	2.6
France (total)	201.80	94.0	6.0

regenerating the forest area when the pathogen is not present (e.g. see Fig. 6). Therefore, under the ash dieback invasion, northern forest managers more frequently face the situation in which they have to switch to alternative forest types due to the collapse of the expected revenues from ash forests.

4.2 Market Impacts

As previously observed at the resource level, the ash dieback invasion reduces the harvested volume of ash species. This is predicted to generate a supply shock whose impacts at the market level strongly depend on the assumption of the degree of substitutability. Firstly, we present the results for the scenarios in which ash wood has a niche regional market due to the wood's physical and aesthetic characteristics, with intermediate or low substitutability (IS-IF and LS-IF). We then discuss the "perfect substitutability" scenario (PS-IF) in which ash products are indistinguishable from other hardwood, so that there are not ash-specific products.

In the scenarios with ash markets, the negative supply shock drives prices upwards. In Table 6, we present the average changes for the entire French territory. At the beginning of the invasion, prices variations are negligible, but according to the simulation results, the prices of ash roundwood will increase by 13–15% in 2030 and by 96–111% in 2060, for the "intermediate substitutability" scenario (IS-IF) and the "low substitutability" scenario (LS-IF) respectively. These percentage variations correspond to predicted prices for ash roundwood in the absence of pathogen mortality. In absolute terms, the difference in the ash roundwood caused by ash dieback is predicted to be between 35 and 41 EUR/m^3 in 2060.

The prices of ash-transformed products are also expected to increase as a consequence of the rise in the price of

Table 6 Ash product price changes expressed in EUR/m^3 and demand changes expressed in m^3 for the "intermediate substitutability" (IS-IF) and "low substitutability" (LS-IF) scenarios

	Intermediate subst. (IS-IF)			Low subst. (LS-IF)		
	2015	2030	2060	2015	2030	2060
Ash roundwood:						
Price variation	0.16	7.86	35.0	0.16	8.43	40.66
	(0.22)	(13.32)	(95.96)	(0.23)	(14.85)	(111.09)
Demand variation	− 118	− 9557	− 40360	− 89	− 5303	− 24134
	(− 0.05)	(− 3.69)	(− 15.30)	(− 0.04)	(− 2.14)	(− 9.1)
Ash sawnwood:						
Price variation	0.17	12.45	56.6	0.29	15.92	69.92
	(0.05)	(3.55)	(18.03)	(0.08)	(4.61)	(22.07)
Demand variation	− 52	− 4292	− 17877	− 37	− 2264	− 10059
	(− 0.05)	(− 3.91)	(− 16.30)	(− 0.04)	(− 2.15)	(− 9.17)
Ash plywood:						
Price variation	0.26	17.23	65.6	0.39	20.9	81.42
	(0.04)	(2.72)	(11.37)	(0.06)	(3.36)	(13.85)
Demand variation	− 6	− 405.22	− 1919	− 6	− 323	− 1673
	(− 0.03)	(− 2.47)	(− 10.39)	(− 0.04)	(− 2.07)	(− 8.76)
Hardwood pulp and fuelwood:						
Price variation	0.01	0.14	0.25	0.01	0.13	0.25
	(0.02)	(0.47)	(0.97)	(0.02)	(0.47)	(0.96)
Demand variation	− 2503	− 66478	− 172130	− 2495	− 65720	− 170479
	(− 0.01)	(− 0.19)	(− 0.46)	(− 0.01)	(− 0.19)	(− 0.46)

Averages across France of regional prices and demand for the years 2015, 2030, 2060. The variations correspond to the case without ash dieback (percentage changes in brackets) the raw material. For ash plywood, the increments with respect to a situation without pathogen spread are estimated to be between 11 and 14% in 2060. This corresponds to an increment ranging between 66 to 81 EUR/m^3 at the end of the simulation period. For ash sawnwood, the increase is predicted to range between 18 and 22%, corresponding to 57–70 EUR/m^3.

On average, the demand for ash roundwood is expected to decrease by 2–4% in 2030 and by 9–15% in 2060. Similar trends are observed for ash plywood and sawnwood. As expected, when consumers have strong preferences for ash products, which cannot be so easily substituted with other hardwood products—as in the "low substitutability" scenario (LS-IF)—the drop in the demand is lower and the new equilibrium is reached at higher prices.

Among other wood products, we noted a reduction in hardwood pulp and fuelwood. There is actually no distinction in the model between ash and other hardwood for these types of products. This is a reasonable assumption since there is no specific demand for ash pulp and fuelwood. Young trees and harvest residuals from ash and other broadleaf species are then added up together into the pulp and fuelwood supply. Therefore, the supply of these products depends on the stock of small and medium diameter ash trees, which are the most affected by ash dieback. For this reason, we forecast a large reduction in the exchanged quantities. Although the demand reduction is considerable, with over 172,000 m^3 lost in 2060, the variation is negligible in relative terms. This is explained by the fact that common ash represents a small fraction of the entire harvested broadleaf species. Pulp and fuelwood prices are then practically unaffected. On average, no significant variations are observed for the other forest products.

Other interesting results emerged when we analysed the impacts at the macroregional level. In Fig. 7, we present the variations in the local supply and in the exports (towards the rest of the world) of ash roundwood for the "intermediate substitutability" scenario (IS-IF). The largest reduction in the supply and export levels is expected to occur in the macroregion Northeast. In the Centre and Southwest macroregion, the local supply increases slightly for some periods before beginning a negative trend. This positive temporal shift in supply is caused by the combination of higher prices and the still moderate impact of the pathogen. Eventually, once the resource is compromised by the pathogen mortality, the supply is expected to drop.

When we assume that ash products are homogeneous with or indistinguishable from the ones made of other

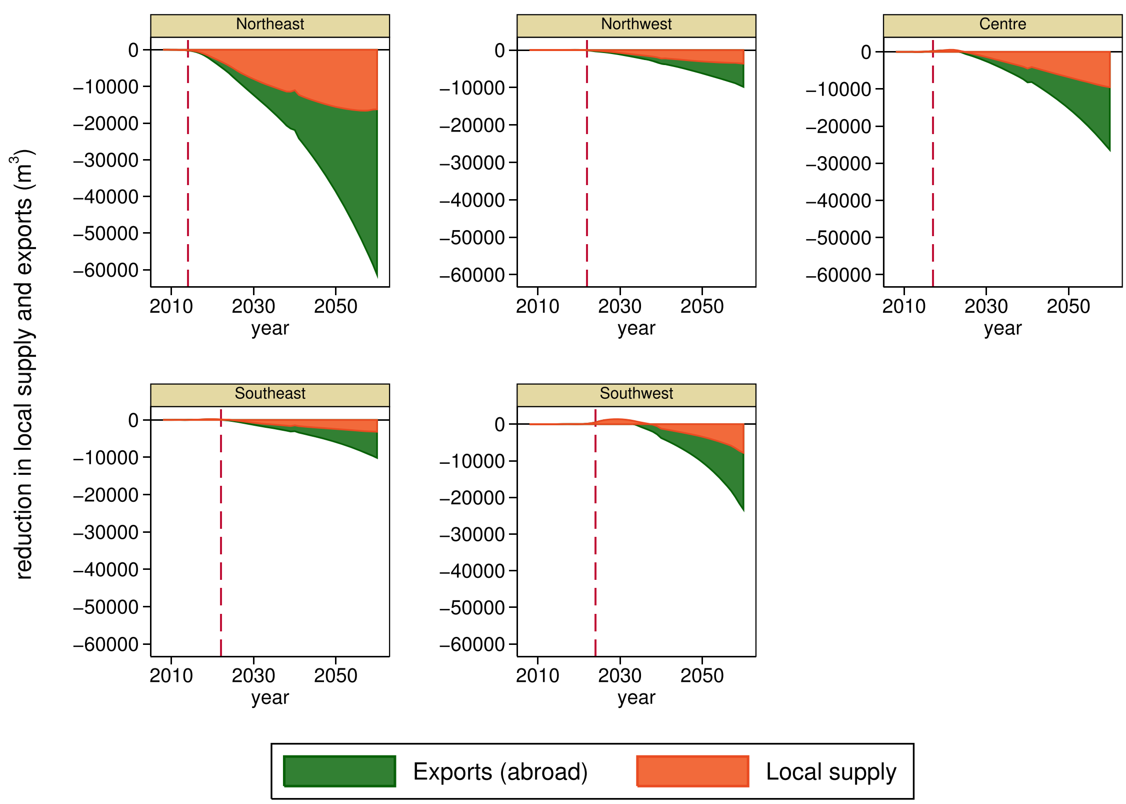


Fig. 7 Variations in ash roundwood local supply and exports to the rest of the world caused by ash dieback in the five macroregional markets (the vertical dashed line indicates the year of full invasion of each macroregion) for the "intermediate substitutability" scenario (IS-IF)

broadleaf species (PS-IF scenario), the economic impact of ash dieback is almost negligible in terms of percentage. This is due to the fact that national ash supply represents a small fraction of the total national hardwood supply. On average, in the period between 2008 and 2060, the hardwood roundwood supply is reduced by 0.5%, with a maximum reduction of 1.5%, corresponding to 106,000 m^3 in 2060. In this scenario, the prices of hardwood roundwood are expected to be 1% higher in 2030 and 4% higher in 2060.

4.3 Welfare Impacts

The reduction in harvesting and the market impacts caused by ash dieback invasion finally impacts the economic agents in the wood sector, whether they are wood producers or consumers. Given that the ash standing volume represents 6% of the total broadleaf species volume, and that ash products represent a niche market, the impact on the surplus of forest products' consumers (not considering amenity values) is rather small. In the "intermediate substitutability" scenario (IS-IF), the annual variation of the wood product consumer surplus caused by ash dieback, i.e. the difference in the consumer surplus with and without ash dieback, is, on average, 0.008% of the consumer surplus.

Producer surplus, in contrast, shows a larger variation, although still small in relative terms. It initially increases due to the effect of higher prices but successively decreases because of the market contraction caused by the establishment of ash dieback (Fig. 8). The producers are expected to lose an average EUR 0.7 million each year of the simulation, which corresponds to a cumulated surplus loss of EUR 37 million for the period 2008–2060. Nevertheless, when we break down the producers' surplus losses across products, we observe that the surplus changes are not homogeneous across productions: some will face surplus reductions while others will actually benefit from the invasion (Table 7). More specifically, the surplus related to ash roundwood as well as pulp and fuelwood production—the two productions that are the most affected by the depletion of the resource—represents the largest part of the producer surplus contraction (respectively EUR 25 million and EUR 20 million over the simulation horizon). In contrast, softwood roundwood production will actually benefit by EUR 9 million from the pathogen invasion because of the crowding-out effect, making these products more competitive compared to others (Table 7, "intermediate substitutability" scenario, IS-IF).

We tested the sensitivity of the producer surplus variation across the different scenarios: results were robust to the expectation assumptions (scenarios IS-MF and IS-PF), whereas they were sensitive to changes in the market structure hypothesis (Table 7): the total producer surplus loss is lower (about EUR 19 million) in the "low substitutability" scenario (LS-IF), whereas in the "perfect substitutability" scenario (PS-IF) it is forecast to be of the same magnitude as the one in the "intermediate substitutability" scenario (about EUR 37 million).

Interestingly, these surplus losses are rather small when compared to the cumulated producer surplus. For example, in the "intermediate substitutability" scenario (IS-IF), the EUR 37 million surplus loss corresponds to 0.07% of the cumulated producer surplus (Table 7). Such a small percentage is the result of two different factors: (i) ash products represent a small share of the entire forest sector. Actually, when we isolate the cumulated surplus related to ash roundwood, the producer surplus loss is expected to be

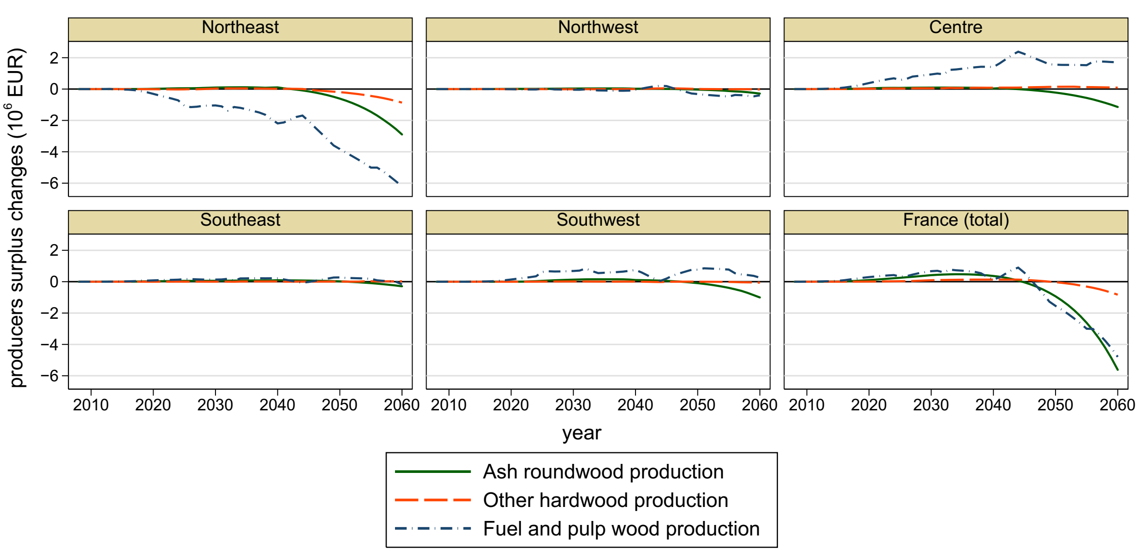


Fig. 8 Producer surplus changes in the five macroregions and throughout France for the "intermediate substitutability" scenario (IS-IF)

Table 7 Cumulated producer surplus losses for the simulated period 2008-2060

	Losses IS-IF		Losses LS-IF		Losses *PS-IF*	
	M EUR	%	M EUR	%	M EUR	%
Ash roundwood	25.2	4.31	4.3	0.76	–	–
Hardwood roundwood	1.3	0.01	1.3	0.01	20.0	0.23
Softwood roundwood	– 9.8	– 0.06	– 9.7	– 0.06	– 9.2	– 0.06
Pulp and fuel wood	20.4	0.07	23.2	0.08	26.2	0.09
Total	37.1	0.07	19.0	0.04	36.9	0.07

Breakdown by primary product for the "intermediate substitutability" (IS-IF), "low substitutability" (LS-IF) and "perfect substitutability" (PS-IF) scenarios

about 4%; and (ii) the surplus losses are mostly concentrated in the last 15 years of simulation.

When we break down the producer surplus losses across the five macroregions, we find that the impacts are not homogeneous (Fig. 8). The Northeast macroregion is the most affected, in particular for pulp and fuelwood production. This is due to the fact that ash dieback arrived earlier in this macroregion and that the mortality among young trees is more severe. In addition, the prices of pulp and fuelwood are not likely to be affected by the ash supply shock. Hence, the producer surplus decreases for this type of product. In contrast, the Centre and Southwest pulp and fuelwood producers are expected to have a surplus gain generated by the invasion. These macroregions are actually less dependent on ash tree for the supply of pulp and fuelwood, since ash standing volume represents a lower percentage of the total standing volume. Similar results are found for the "low substitutability scenario" (LS-IF).

Considering all of the forest products together over the simulation horizon, only two macroregions exhibit a negative annual loss in the producer surplus: the Northeast, undergoing a loss of EUR 0.58 million per year, and the Northwest, losing EUR 0.02 million per year. In the last 15 years, the annual surplus losses are expected to be, on average, EUR 1.46 million and EUR 0.08 million per year, respectively. In contrast, the Centre, Southeast and Southwest are predicted to face, on average, a higher annual surplus with the pathogen invasion. Over the period 2008-2060, the gains are about EUR 0.27 million per year for the Centre, EUR 0.05 million per year for the Southeast and EUR 0.1 million per year for the Southwest.

5 Discussion and Conclusions

In this work, we captured several important aspects of the pathogen invasion: firstly, it is possible to break down the total volume losses into direct pathogen mortality and the behavioural adaptation of the forest managers (i.e. regeneration and harvesting choices); secondly, in contrast with previous studies that used current market prices to evaluate the resource loss, we endogenously determined price dynamics via a recursive partial equilibrium model; thirdly, by using a spatially explicit model, we were able to show that the pathogen impacts are not homogeneous across regions and depend on the resource distribution, pathogen spread and transport-cost structure; finally, we identified surplus changes and surplus redistribution in the forest sector. In line with previous works [13, 14], our findings stress the importance of integrating the biophysical and economic aspects of the invasion, in order to fully understand the overall impacts. This is even more important given the increasing number of forest disturbances that are expected to threaten the forest sector [42].

As far as the ash dieback invasion in France is concerned, we project significant volume losses at the resource level. The Northeast will be the most affected macroregion. The share of ash in the north-eastern landscape is expected to drop from about 7% of the pre-invasion period to 1.5% at the end of the simulation horizon. Overall, since we account for the natural regeneration in the model, common ash is not going to completely disappear from the landscape.

According to our simulations, forest managers will react to the invasion by switching from ash to other forest species when regenerating the harvested areas. These management decisions probably accentuate the overall reduction of the standing volume on a mid-term horizon, which is expected to be non-negligible if control methods remain unavailable. Specifically, we project that the *adaptation* effect represents an average of 4–7% of the total volume reduction over the simulation horizon, but could account for almost one-tenth of the total volume loss in some macroregions.

At the market level, prices are expected to rise following the negative supply shocks. These results are sensitive to the degree of substitution between ash and other hardwood products. The local supply generally decreases, particularly in the Northeast macroregion where the resource is initially more abundant and with the longest presence of the disease. In the Centre, Southwest and, to a lesser extent, Southeast macroregions, the local supply is initially larger with the pathogen presence than without it. This effect is small but interesting because it represents an indirect anthropic component of ash volume reduction. The high ash product prices in the market accelerate the harvesting of ash where it is still present but, at the same time, the low expected return—caused by the large expected mortality—drives the regeneration choices towards either other broadleaf species or conifer species. However, in our simulations, the projected ash price increments (net of the transportation costs) are not sufficient to trigger a boost in ash harvesting capable of drastically reducing the resource level.

As far as the sector welfare is concerned, ash dieback is not expected to have major impacts. This is not a surprising result given that ash products represent only a small fraction of the forest sector. The producers are expected to face surplus gains in the first part of the invasion (before 2045), since the price increments more than compensate for the reduction of the marketed quantities. However, once the ash resource is heavily reduced—in 2045, the volume losses will account for about 65%—we project welfare losses that will monotonously increase thereafter.

Another important aspect emerged from the welfare analysis as to how ash dieback affects the welfare redistribution. By altering the resource distribution and the market equilibria across space and time, the invasion has asymmetric effects across product types and macroregions. For example, the producer surplus related to fuelwood and pulp production is decreasing very rapidly in the Northeast macroregion and, at the same time, increasing in the Centre and Southwest. This can be explained by the fact that ash wood represents a non-negligible resource for producing pulp and fuelwood products in the Northeast, whereas it is almost absent in the Centre. Consequently, pulp and fuelwood producers will benefit from small price increments caused by ash dieback.

There are certain aspects that the model was not able to capture and the lack of certain data requires us to be cautious when interpreting the results. Firstly, when interpreting the *adaptation* effect and all of the other cumulated impacts reported (e.g. volume and welfare losses), it is important to notice that all of these indicators are affected by the choice of the simulation horizon. By increasing the end of the horizon, we are likely to have larger welfare and volume losses, as well as a greater impact of the *adaptation* effect. We arbitrarily limited the simulation to 2060, which is considered to be a sufficiently long horizon to capture the key features of the invasion. We preferred not to extend the simulation beyond 2060 because the model would not be able to capture possible structural economic and ecological changes.

Secondly, due to the lack of data and knowledge about certain biophysical and ecological aspects, we did not consider the impacts of ash dieback on environmental service provision. Our forecast of welfare changes therefore only accounts for the impacts on the timber and wood-based product markets. As a consequence, the harvesting and regeneration choices in this study do not generate negative externalities because all information is transmitted through the market prices. Nonetheless, it is not unlikely that the drastic reduction of the ash population reduces biodiversity and the recreation potential of certain areas. Furthermore, by harvesting ash trees, there is the risk of removing potentially genetically resistant individuals, as observed in recent studies [26]. In this case, the forest manager's adaptation decisions that our model highlighted—e.g. not replanting ash and, in some cases, harvesting it more intensively—will indeed cause negative externalities on the environmental service provision and forest health. Consequently, it will be important to integrate these aspects in future analyses once models linking ash trees and the environmental service provision, as well as better data on the role of resistant ash trees, are available.

Thirdly, the spread model does not take the effects of habitat characteristics such as temperature and moisture conditions for the survival of the pathogen into account because the biological mechanisms are not yet totally clear. It is even possible that the higher temperatures in southern France may act as a natural barrier to the ash dieback spread [36, 43, 44]. If this hypothesis is confirmed, we expect to have larger welfare redistribution from the northern marcroregions towards the southern marcroregions.

Fourthly, the ash dieback spread is assumed to be exogenous. In other words, the spread model does not depend on the ash tree distribution and, in turn, on forest management. To our knowledge, an endogenous spread model is not yet available in the literature. However, given the high speed of the invasion front and the nature of the airborne spread, we believe that the spread model is able to provide a fair representation of *Hymenoscyphus fraxineus* invasion.

Fifthly, the partial equilibrium nature of our economic modelling framework fails at taking all economic impacts into account. In particular, the impacts on tree nurseries is not accounted for. At the national scale, the overall revenues from ash plants sales in France dropped from about EUR 168,000 in 2015–2016 to EUR 60,000 in 2016–2017 [45, 46]. Though this is far lower than the total welfare impacts on the wood sector, it can nevertheless put at risk an economic sector already weakened by recurring climate crisis.

In conclusion, we believe that this paper contributes to bridging the gap in the literature of invasive species in the forest ecosystem by integrating ecological and economic models in a dynamic and spatially explicit setting. Although some aspects of the model should be improved, we believe that this work presents a consistent tool to approach this complex problem. This framework can easily be applied to different cases (different tree species as well as multiple bioinvasions) once the host volume distribution and spread and mortality models are provided.

Eventually, one major direction for future research is to better link biotic hazards to climate conditions. It is indeed very likely that the occurrence and the speed of the invasion as well as the tree vulnerability depend on a wide range of conditions (e.g. storm, fire, drought, other biotic hazards), resulting in a ”cascading” risk framework. Accounting for this cascading framework within an integrated ecological and economic model will increase the understanding and the assessment of climate change impacts on forests and the forest sector.

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Appendix A: Ash Volume Distribution Estimation

A.1 The Ash Volume Spatial Distribution

In order to analyse the impact of ash dieback in France, we adapted the original French Forest Sector Model by including ash forest as an additional forest type. The first step was to estimate the ash volume distribution in each cell. We used geostatistical techniques to spatially predict the ash volume distribution in unsampled areas based on the identified spatial structure derived from sampled locations [47]. Specifically, we used the *kriging with external drift* method in which the predictions from a regression model are adjusted using the spatial correlation between neighbouring observations as a function of distance. Kriging techniques have been previously used to predict forest biomass and other forest characteristics over large areas [27, 28].

Data on ash populations was taken from the French National Forest Inventory (FNFI) carried out by the French National Institute of Geographic and Forest Information (IGN) for the years 2006-2010 [29]. We know the forest cover type and structure, the number of trees for each species, tree volume, diameter at breast height and a weight for computing the volume per hectare for each sample plot. All together, we had a total of 30,879 inventory plots, and ash was present in about 10% of the plots.

In the regression model, we used the ash volume per hectare from the inventory plots as the dependent variable. For independent variables, we selected the soil water deficit as defined in [48], the soil pH obtained from the portal on forest spatial data, *SILVAE* [49], and the elevation, as well as a categorical variable representing the 83 different types of ecological regions present in French forests. We had no observations of the dependent variable in three ecological regions, so they were not included; *ser1* was used as a reference. The digital elevation map and the map of the French ecological regions were downloaded from the IGN website (www.geoportail.gouv.fr).

We divided the sample into four subsets, each containing observations on ash trees measured in the four different forest types, corresponding to the ones defined in FFSM: conifers (C), broadleaf high forest (BH), broadleaf coppice (BC) and broadleaf mixed high forest and coppice (BH&C). We then ran a separate linear regression model for every subset. This was done to improve the prediction performance since the observed spatial structure of the residuals was not homogeneous across forest types. In Table 8, we present the estimated coefficient for the regression models that generate the residuals that were then used to derive the spatial structure of the ash volume via kriging.

Once obtained the residuals from the linear regression (Table 8), we applied the kriging procedure to adjust the prediction of the model in unsampled locations based on the spatial correlation structure between neighbouring observations expressed as a function of the distance. In other words, we fitted the theoretical variograms to the empirical ones to determine the variogram parameters. We used an exponential variogram model for the broadleaved high forest and the broadleaved high forest and coppice, whereas we used a spherical variogram model for the broadleaved coppice and the coniferous forest types (Fig. 9).

Successively, ash volumes per hectare were successively predicted on a 1-km^2 grid covering the entire French territory, with the exception of Corsica for which we did not have data. The computation was carried out using the *gstat* package in R [50].

Once we estimated the ash volume per hectare within each forest type, we multiplied it by the forest area of the

Table 8 Estimated coefficients of the linear regression model used in the kriging with external drift to predict the spatial distribution of the ash volume per hectare in the four forest types: BH = broadleaved high forest; BH&C = broadleaved mixed high forest and coppice; BC = broadleaved coppice; C = coniferous

	BHF	BHF&C	BC	C
(Intercept)	− 32.4991[c]	− 10.2244[b]	− 4.0846	− 5.8849[c]
elev	− 0.0142[c]	− 0.0084[c]	− 0.0001	− 0.0014[c]
ph	10.3336[c]	4.7281[c]	1.6549[b]	1.7069[c]
wstress	− 0.3582[c]	− 0.2958[c]	− 0.0518	− 0.059[c]
ser2	2.3035	2.188	9.1473[b]	0.7459
ser3	3.522	5.0111	3.3169	1.9022
ser4	6.6058	5.0279	0.8656	1.486
ser5	1.4887	10.3381[a]	− 0.7101	0.9244
ser6	0.9994	9.5493[a]	6.3805[a]	0.1102
ser7	7.5809[a]	13.8857[c]	14.8438[c]	− 0.1061
ser8	11.4152	2.9445	–	6.8507
ser9	25.4005[c]	52.6431[c]	25.5944[c]	− 2.0162
ser10	11.196[b]	51.8077[c]	− 5.2229	− 2.4782
ser11	6.0549	14.3189[b]	26.5387[c]	− 0.2321
ser12	3.0126	9.4743[b]	1.0741	0.4573
ser13	4.1392	14.7144[c]	8.9098[a]	1.212
ser14	9.2674[b]	18.5891[c]	− 0.0477	0.2911
ser15	14.8345[c]	10.0005[b]	3.95	0.0244
ser16	32.9728[c]	27.2185[c]	21.2559[c]	0.7451
ser17	2.6726	8.6838	− 1.7999	− 1.1439
ser18	5.9919	12.6412[c]	7.0064	4.1426
ser19	− 3.0385	0.5816	− 1.2594	− 0.8239
ser20	0.4613	0.06	− 3.1809	− 0.9375
ser21	1.7738	4.219	− 1.1247	1.4303
ser22	1.6261	4.1756	− 1.3924	0.5023
ser23	6.3774	3.3732	2.2495	1.1258
ser24	− 1.1776	0.8274	− 1.6518	− 0.3862
ser25	− 4.5437	2.521	− 2.8072	0.1065
ser26	− 4.5123	− 2.5968	− 3.6414	4.58 [a]
ser27	3.1908	1.3574	− 0.2273	− 0.5518
ser28	− 5.1204	− 2.4574	–	− 0.2307
ser29	6.5978	7.2841	–	2.5593
ser30	− 8.6655[b]	− 1.9172	− 0.8001	0.8973
ser31	4.0012	6.2596	− 1.5285	0.2738
ser32	4.6004	16.4395[c]	− 4.0579	− 0.8068
ser33	18.2528[c]	13.9468[a]	–	7.095[a]
ser34	4.1451	2.101	2.8783	5.9815
ser35	20.7537[c]	7.609 [a]	5.7823[a]	− 0.1529
ser36	8.7376[b]	10.784[a]	− 2.4012	2.9199[c]
ser37	2.4509	2.6024	− 2.7766	0.6683
ser38	7.6196	8.2965[b]	3.8266	2.1847
ser39	4.1806	1.8427	− 5.2907	− 0.0039
ser40	11.603	3.2425	− 2.3248	1.1601
ser41	− 12.6479	13.4694[c]	1.7259	− 0.5908
ser42	− 9.2304	48.7002	− 4.0622	− 1.6936
ser43	− 3.0634	12.5094[b]	5.6477[a]	− 0.96
ser44	− 3.9625	0.6709	− 1.0246	− 0.361
ser45	2.2835	2.573	0.3612	1.3203
ser46	− 2.6745	1.6324	− 2.8906	0.5882

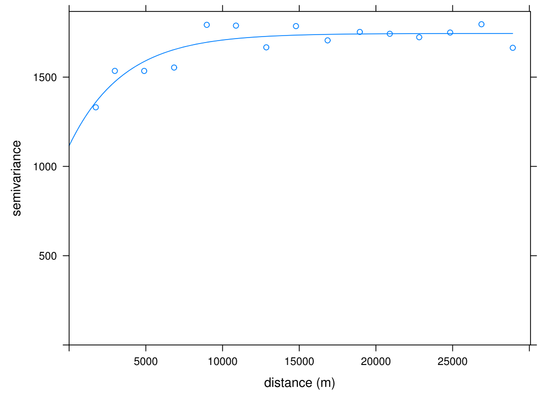
Table 8 (continued)

	BHF	BHF&C	BC	C
ser47	0.2966	1.7621	− 0.6571	0.6363
ser48	− 9.8133[b]	− 0.6352	1.4985	0.6083
ser49	− 15.738[c]	− 2.1558	− 4.4046	− 1.6713
ser50	− 10.3202[b]	1.5828	− 4.0321	− 2.3463
ser51	− 7.3223	4.7334	16.6607[c]	1.2161
ser52	− 0.4166	− 0.2746	− 2.3858	− 0.4274
ser53	− 5.8716	3.7591	− 3.3007	12.0067[c]
ser54	− 2.138	− 1.1265	− 2.8737	− 0.0914
ser55	0.4831	2.0443	− 3.2147	0.2567
ser56	14.6112[c]	11.3274[c]	− 2.6046	0.9781
ser57	− 0.7341	− 0.3191	− 3.156	− 0.1883
ser58	1.4139	23.5714[c]	− 2.1831	0.5089
ser59	13.9638[b]	8.7969[a]	− 0.6288	1.5477
ser60	9.6917[a]	7.1728	11.2863[c]	2.7443[b]
ser61	0.8366	6.8188[a]	0.2399	0.074
ser62	− 9.4333	− 2.2071	− 4.8933	− 2.5554[a]
ser63	2.7459	0.6167	− 3.0998	− 0.0844
ser64	10.1643	15.5131[c]	− 2.2826	1.1597
ser65	− 1.8956	7.0479	1.2163	0.1065
ser66	2.5721	7.7197	− 3.2534	1.2358
ser67	12.2686[a]	− 0.3063	− 3.7354	3.0878[b]
ser68	19.6439[b]	15.2686[a]	11.9964	− 2.125
ser69	− 14.2307[b]	− 1.8753	− 5.8347	− 2.9133[b]
ser70	1.425	4.9776	− 5.1522	− 1.9705
ser71	− 6.5108	14.1339	−	− 1.896
ser72	− 2.4568	13.3627[c]	− 2.4408	− 1.0401
ser73	− 3.8136	18.5692[c]	− 1.9524	− 0.2603
ser74	− 10.9625	− 0.5607	− 4.281	− 1.8152
ser75	1.7744	12.513[c]	8.8127[b]	0.7929
ser76	− 0.3011	8.5166	10.3273[b]	− 0.7619
ser77	− 12.0782	− 2.4715	− 4.6452	− 2.2553
ser78	− 14.8841	3.9139	− 4.3465	− 1.896
ser79	− 14.9531[a]	− 0.6564	− 4.2932	− 2.0209
ser80	− 12.951	2.8622	− 4.4428	− 1.5979
ser81	− 8.2606	1.7116	− 4.6845	− 2.0741
ser82	− 2.7281	6.7675	− 2.6178	− 0.4214
ser83	− 15.2116	0.546	− 4.9076	− 2.1772
R^2	0.07	0.08	0.08	0.03
N of observations	9993	8286	2995	283

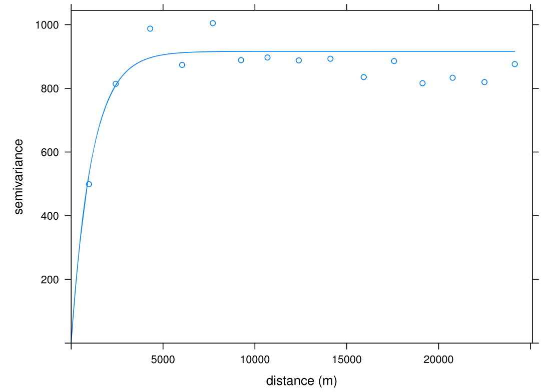
[c] p-value < 0.01, [b] p-value < 0.05, [a] p-value < 0.1

respective forest type in each pixel. By doing this, we were able to calculate the total ash volume per pixel. The forest-type areas were computed from a forest cover type map [51]. The total ash volume map was finally rescaled on a 8-km^2 grid (Fig. 2) in order to correspond to the Forest Dynamics module (FD). Finally, we computed the total ash volume per pixel, we removed it from the general ”broadleaf” volume used in the original FFSM.

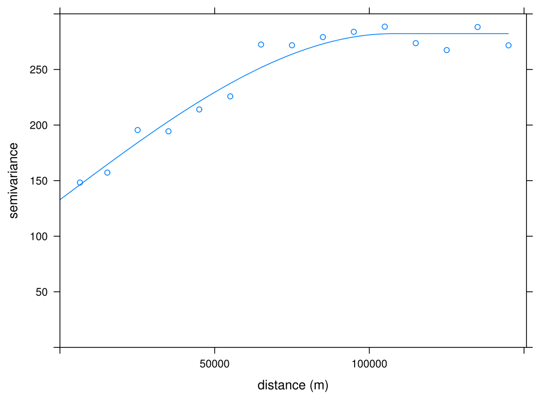
In the second step, we had to broke down the total ash volumes per cell by diameter classes, in order to match the data



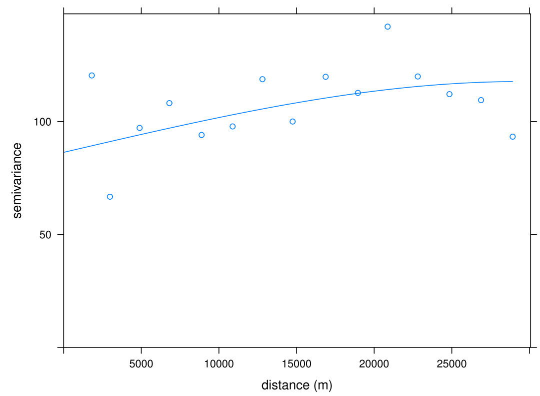
(a) Broadleaved high forest



(b) Broadleaved high forest and coppice



(c) Broadleaved coppice



(d) Coniferous forest

Fig. 9 Experimental and fitted variogram for ash volume per hectare in the four forest types

structure in FD module. Following the example of [52], we assumed that the volume distribution across diameters could be approximated by the 3-parameter Weibull distribution, with the third parameter (representing the minimum diameter) fixed at 7.5 cm. This is the minimum diameter measured in the forest inventory. The parameters were estimated via maximum likelihood for each ecological region using the FNFI data.[7] The volume within each diameter class was finally derived by multiplying the total ash volume in each pixel by the share of total volume within each diameter class obtained from the cumulative distribution function.

[7]It was not possible to directly estimate the Weibull parameters for 17 ecological regions because they did not have enough observations, i.e. less than 30 data points. When it was possible, these regions were merged with similar (in terms of soil pH, water stress, forest type composition and elevation) low-observation neighbouring ecological regions and the parameters were then estimated. This aggregation was not possible for three ecological regions due to the lack of other neighbouring ecological regions with low observations. In these cases, we used the estimated parameters from a similar neighbouring ecological region with enough observations as a proxy.

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