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Economic analysis of adaptation options toward drought-induced risk of forest dieback: financial balance and/or carbon balance

THESE

pour l'obtention du grade de Docteur en Sciences Economiques

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“Twenty years from now you will be more disappointed by the things you didn’t do than by the ones you did do. So throw off the bowlines. Sail away from the safe harbor. Catch the trade winds in your sails. Explore. Dream. Discover.”

« *Dans vingt ans vous serez plus déçus par les choses que vous n'avez pas faites que par celles que vous avez faites. Alors sortez des sentiers battus. Mettez les voiles. Explorez. Rêvez. Découvrez.* »

Mark Twain

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Introductory chapter

Context and motivation

Forests are ecosystems that play an important role in the adaptation of the society to climate change ("forests for adaptation", Locatelli *et al.*, 2010). They provide ecosystem services that contribute to human well-being and reduce social vulnerability. In addition to timber production and heritage value (*e.g.,* biodiversity, recreation), forests store carbon, protect water resources and soil from erosion, and protect against natural hazards (*e.g.,* landslide in mountainous areas, flood in coastal areas) *inter alia*. Their long growth cycle makes them vulnerable to natural risks. Up to now, forests have adapted to cope with a variety of disturbances coming from the direct environment, *i.e.,* abiotic disturbances (*e.g.,* climate, soil, topography, chemical factors) and from the interaction with other living beings, *i.e.,* biotic disturbances (*e.g.,* pests and diseases, competition).

Presently, the pace of climate change is accelerating too fast for the natural and spontaneous forest adaptation process to offset many negative impacts of climate-induced changes. The increase in atmospheric concentrations of carbon dioxide (CO_2) has been a major contributor to global climate change (IPCC, 2013). Concentrations of CO_2 have increased by 40% since the 1950s, thus leading to many consequences never observed before. These include the increase of global mean temperatures and the intensification of contrasts between wet and dry regions/seasons (IPCC, 2013). All these changes can induce short-term positive effects on forest productivity through CO_2 fertilisation (Schröter *et al.*, 2005) as well as long-term negative effects such as increased frequency, duration, and intensity of mean and extreme natural events (Dale *et al.*, 2001). More specifically, growing seasons extend through temperature increments, and, under favourable precipitation conditions, forest productivity increases as growing seasons, atmospheric carbon concentrations (to some extent), and nitrogen deposition increase (Schröter *et al.*, 2005). However, in the event of repeated and severe drought episodes, forests cannot take advantage of these environmental factors: There is a trade-off between growth performance and resistance or even survival (McDowell *et al.*, 2008). In France, the extreme drought events of 1976 and 2003 caused great damage to the forest, both immediately and long after the drought episodes (Bréda *et al.*, 2004). The 2003 drought caused more damage than that of 1976 as the heat wave occurred simultaneously with a water shortage that induced stomatal control and loss of canopy refreshment (Bréda *et al.*, 2006). In 2018, an even stronger drought event affected a larger area of Europe than in 2003 (Buras *et al.*, 2020). These examples show how water resource is a key factor for forest productivity and health and how the timing, duration, and intensity of water shortage is one of the principal sources of stress.

From the ecophysiological point of view, drought is a reduction of the water availability in the soil, sufficiently severe to prevent the optimal functioning of trees due to insufficient precipitation, high temperature inducing high evapotranspiration, and large water uptake by trees (Bréda *et al.*, 2004). Drought is a natural phenomenon affecting forest productivity and health especially when its intensity is extreme (Seidl *et al.*, 2011). In Europe, trees suffer from severe water shortages that typically occur in early summer (Bréda and Badeau, 2008). While drought is considered as one of the main damaging abiotic risks (Rouault *et al.*, 2006), its induced impacts on forest health have been underestimated for a very long time due to inconspicuous damage at first sight (Spiecker, 2003). Water shortages result in a variety of short- and medium/long-term effects, which can be more or less severe (and visible) depending on species, *e.g.,* closure of stomata leading to reduced transpiration and carbon assimilation, slower growth, abnormal defoliation, xylem embolism, and mortality of buds, branches, roots or the entire tree.

These tree-level regulations or permanent damages may impact entire stands, and ultimately, entire ecosystems. Indeed, at the stand level, the loss of growth, which is proportional to the drought intensity, induces a loss of productivity. At the ecosystem level, the lack of water supply reduces most of the biological cycles and affects the functions of the forest. This leads to a loss of ecosystem services, such as wood production and carbon sequestration. In terms of socio-economic impacts, drought as well as other disturbances such as storms, generate financial losses that may be concentrated at the stand level or may affect the whole wood chain sector: loss of marketability, decrease in future stand value, additional cost associated with forest restoration, and loss of hunting revenues and other regular sources of revenue (Birot and Gollier, 2001). Additionally, the decrease in the supply of ecosystem services results in economic losses for forest owners, as well as a loss of welfare and amenities for the society as a whole (Schröter *et al.*, 2005; Ding *et al.*, 2016).

While extreme drought events are thought to be rare phenomena, their frequency might increase in the future because of climate change (IPCC, 2013). Additionally, spontaneous forest adaptation will most likely be not fast enough to keep up with the pace and the intensity of this global change. In a context of increasing risk, forests need to adapt in order to reduce their vulnerability to drought-induced dieback (IPCC, 2001; “adaptation for forests”, Locatelli *et al.*, 2010). In France, three-quarters of the metropolitan forests are privately owned (IGN[1], 2019). This represents 12.5 million hectares owned by 3.5 million private owners, with more than 60% of them owning less than one hectare. Therefore, the adaptation of the French forests heavily relies on private owners. Despite being aware of climate change and its impacts, only a minority of forest owners adapt their forests in a proactive way (Sousa-Silva *et al.*, 2016; Andersson and Keskitalo, 2018). Ninety-five (95%) of them do not have a management plan (CNPF[2], 2019). In the near future, the increase of climate-induced damages associated with greater financial losses is likely to either discourage forest investments, foster forest abandon (which, in turn, will result in a loss of forest functions) or, to the contrary, stimulate the implementation of adaptation strategies in response to the forest crisis.

Since Smit *et al.* (2000), various definitions of adaptation have been proposed in the literature dedicated to climate change. In the context of global change, adaptation usually refers to a process, action or outcome in ecological and socio-economic systems in order for the system to better cope with, manage or adjust to actual or expected changing conditions, external stress, hazard, risk or opportunity, and its related effects or impacts (Smit *et al.*, 2000; Smit and Wandel, 2006). While climate change induces uncertainty with regard to the impacts and outcomes of adaptation, certain losses can be avoided by implementing the appropriate adaptation strategies. These strategies can be divided into two categories of risk management: market-based adaptations and management-based adaptations. Market-based adaptation refers to insurance, *i.e.,* financial compensation for losses and/or costs associated with recovery actions taken in an attempt to return to the pre-disaster status. Management-based adaptation refers to a decision making approach aimed at managing a crisis after a disaster and anticipating actions to prevent risk impacts on forest stands. Different typologies were defined depending on key attributes, such as the purposefulness (autonomous *vs*. planned), the timing (proactive *vs*. reactive), the scope (incremental *vs*. transformational) or the goal (resistance *vs*. resilience *vs*. transition) of the adaptation (Fischer, 2019). The World Bank (2010) also proposed a categorisation based on

[1] French National Forest Inventory.

[2] French National Center for Privately-Owned Forests.

soft *versus* hard adaptation. The following classification was used in this thesis: incremental, transitional, and transformational adaptations (Roggema *et al.*, 2012; Ramirez-Villegas and Khoury, 2013). Incremental adaptations entail making small changes in current contexts in order to avoid disruptions (Fischer, 2019). Local adjustments (stand level) are made based on the observed impacts (*i.e.,* reactive adaptation). Transformational adaptations entail making large-scale changes (whole sector) or changes that are new to a particular region or system; or changing the broader biophysical, social or economic system (Fischer, 2019). These planned and long-term changes need more resources (*e.g.*, financial, technical) and induce more uncertainty than the two other types of adaptation. Transitional adaptation lies between incremental adaptation and transformational adaptation. Gradual and continuous change processes are implemented based on the observed impacts, as it is the case in the incremental adaptation. However, depending on the site conditions and/or the intensity of the damages, the outcomes of incremental adaptation can be insufficient. The system is thus transformed, but not fundamentally, as it would be with a transformational adaptation. Instead, the transformation allows for the establishment of a new steady state characterized by a higher level of complexity or quality.

Private owners can protect their forests through a combination of the above-described adaptation strategies. Therefore, to cope with climate change-related risks such as drought-induced risk of forest dieback, Fuhrer *et al.* (2006) emphasized the need for management-based adaptation strategies supplemented with new insurance contracts (market-based adaptation). Indeed, forest management is the main tool for managing vulnerability at the stand level (Jactel *et al.*, 2009). Silvicultural operations tailored to species composition and overstory structure have the largest influence on both the biotic and the abiotic risks faced by European forest stands. Such operations can achieve forest management objectives at the same time as minimising risks (Jactel *et al.*, 2009). Indeed, water-saving forest management can mitigate the intensity and duration of water shortage periods and their related damages; and, therefore, increase the trees' adaptive capacity to a changing climate (Bréda and Badeau, 2008).

Different management-based adaptation strategies are recommended in order to improve the water consumption efficiency of the forest stand and thus its resistance to drought risk (Spittlehouse and Stewart, 2003). First, the following incremental adaptation strategies can be identified: reduction of rotation length and reduction of stand density. While the former allows for a reduction of the time of exposure to drought events (Spiecker, 2003; Bréda and Peiffer, 2014), the latter reduces the water demand (Aussenac and Granier, 1988). Indeed, the reduction of stand density causes a reduction of the leaf area (Bréda *et al.*, 1995), which decreases intensity and duration of water deficits, and increases water availability for the remaining trees (Spiecker, 2003; Bréda and Badeau, 2008). As water shortage is mitigated, the growth recovery of trees is improved (Schmitt *et al.*, 2020). Second, the increase of stand diversity can promote the development of more stable forest stands able to hedge from climate fluctuations and disturbances. This transitional adaptation strategy can be implemented by mixing the current species of the stand with one or more introduced species, as a means to foster tree complementarity (Forrester, 2014). However, an improper mixture can also have some adverse effects such as an increase in the competition for water resources (Grossiord *et al.*, 2014; Bonal *et al.*, 2017). Another possibility is to keep the current species while modifying the structure of the stand by mixing different diameter classes (or age). This strategy has been associated with increased wind resistence (Hanewinkel *et al.*, 2014) and greater resilience to natural hazards (Jacobsen and Helles, 2006). Third, a possible transformational adaptation can be the substitution of the current species by a more suitable one, which can be more drought-tolerant and/or more productive (Keskitalo and Carina, 2011). It is likely that some geographic areas will become favourable to the establishment of species not present initially and/or unsuitable for historically present species (Martin *et al.*, 2015). However, adaptation efforts can increase the vulnerability of oneself and others (instead of decreasing it), an issue known as maladaptation (Barnett and O'Neill, 2010; Juhola *et al.*, 2016). Insurance can be another strategy by sharing and thus reallocating risks (Raviv, 1979). The principle consists of transferring the risk from the insured to the insurer: The forest owner receives an indemnity in case of disaster occurrence, in exchange for the payment of an annual insurance premium. In most of the European countries, forest insurance contracts are available for storm and/or fire risks. Recommendations are made to use insurance as a vehicle to finance climate resilience and adaptation by the Global Agenda Council on Climate Change (2014), the Organisation for Economic Cooperation and Development (2015), the United Nations Framework Convention on Climate Change (Article 4.8 of UNFCCC), and the Kyoto Protocol (Article 3.14).

Forests play a major role in climate change mitigation through carbon sequestration via photosynthesis ("forests for adaptation", Locatelli *et al.*, 2010). Indeed, forests contain 80% of all aboveground carbon and 40% of the belowground terrestrial carbon (*i.e.,* 1146 GT of carbon), of which 14% is in temperate forests (Dixon *et al.*, 1994). Coping with climate change-related risks can simultaneously mitigate climate change by maintaining or increasing these carbon stocks. Moreover, regarding carbon stocks in forests, there is a growing concern about how this mitigation capacity can be maintained as water availability decreases (Granier *et al.*, 2007) and drought risk increases (Locatelli *et al.*, 2010; Kolström *et al.*, 2011). Choat *et al.* (2012) observed that drought-induced forest diebacks are occurring not only in arid regions, but also in wet forests typically not exposed to this type of risk. Longer droughts and higher temperatures can negatively impact the carbon-sink role played by forests (Allen *et al.*, 2010) and even turn forests into carbon sources (*e.g.*, tropical forests) (Choat *et al.*, 2012). Therefore, mitigation of climate change is not possible without adaptation. Finally, in a context of international agreements where the forest sector is considered an essential lever to achieve climate goals (Kolström *et al.*, 2011), the French government has made several commitments, including the Paris Agreement and attaining carbon neutrality by 2050. These commitments are thus part of French forest and timber program objectives (PNFB, 2016-2026) that aim at decreasing the uncertainty related to climate change while promoting a more dynamic and sustainable silviculture; one that increases the carbon storage capacity of the French forest stands and contributes to the economic growth of the forest sector.

Research questions and objectives of the thesis

In a context where forest management has become a way to mitigate increased drought risks resulting from climate change, where public requirements in terms of carbon storage has become more stringent, and where environmental concerns are increasing, many questions arise: Is there an economic interest for forest owners in implementing adaption strategies? What are the effective adaptation options to face a projected drought-induced risk? What are the costs and the benefits of these relevant adaptation strategies? How do these strategies differ in terms of carbon sequestration? Is a forest insurance contract against drought-induced risk of forest dieback effective? The objective of this thesis is to try to answer these questions.

More specifically, this thesis aims at (i) testing and compare different management-based adaptation options for drought reduction in forests in order to avoid projected risk of dieback, both in terms of financial balance supported by the forest owner and the carbon balance supported by the society, and (ii) proposing a new market-based adaptation option in the form of an insurance contract against drought-induced risk of dieback.

In the literature related to the first objective of this thesis, few studies have tackled the issue of adaptation to climate change using a forest economics approach. Such studies have typically performed a cost-benefit analysis through the maximization of the net present value (NPV) or Faustmann's land expectation value (LEV). In this context, several strategies are then analysed. Brunette *et al.* (2014) showed that the shift to better-adapted species to climate change maximised LEV in a case study in France. The species mixture in Germany was analysed by Yousefpour and Hanewinkel (2014). They demonstrated that a balanced decision can be found by establishing beech regeneration in 46% of Norway spruce stand and storing 39.5 kg/ha carbon in forest biomass to adapt to future climate change. More recently, Bréda and Brunette (2019) focused on the reduction of rotation length in France as a potential adaptation strategy towards a drought-induced risk of Douglas-fir dieback. They compared three different adaptation strategies (absence, immediate, and delayed adaptations) and showed that adaptation (immediate or delayed) gives always a better economic return than the absence of adaptation. This short literature review reveals that past articles always focused on one strategy at a time. Only Jönsson *et al.* (2015) compared different adaptation strategies against storm risk, but none of the papers analysed combinations of adaptation strategies. Drought-induced risk of forest dieback is often overlooked in economic analyses even though it is one of the most damageable disturbances for forests. To the best of our knowledge, only one article deals with the drought-induced risk of forest dieback (Bréda and Brunette, 2019). Moreover, in this context of climate change, few studies have considered carbon loss in addition to economic loss (Yousefpour and Hanewinkel, 2014; Müller *et al.*, 2019), and climate scenarios are rarely considered.

The literature related to the second objective of this thesis deals with another strategy, forest insurance. Holecy and Hanewinkel (2006) were the first to propose an actuarial model serving as a basis to calculate premiums to insure German forest against single or cumulative damaging factors. They highlighted the main role of the stand age and the total insured area in the computation. Several studies followed with the same approach and similar conclusions (Pinheiro and Ribeiro, 2013; Brunette *et al.*, 2015; Sachelli *et al.*, 2018). A second stream of literature appeared with theoretical studies, which extended the classical insurance economics model proposed by Mossin (1968) with the specificities of the forest management issues (Brunette and Couture, 2008; Brunette *et al.*, 2017). Another part of the literature deals with the estimation of the willingness to pay (WTP) for forest insurance. Brunette *et al.* (2013) were the first to assess the WTP for French forest owners in different scenarios regarding public compensation, and proved the negative impact of these compensations on WTPs. Several papers follow and estimate this WTP for foresters in China (Dai *et al.*, 2015; Qin *et al.*, 2016), USA (Deng *et al.*, 2015) and Germany (Sauter *et al.*, 2016). Finally, a recent study proposed to extend the classical forest economic model setting, the Faustmann optimal rotation model (Faustmann, 1849) under risk (Reed, 1984), to the insurance of storm risk in forest (Loisel *et al.*, 2020). The results suggest that as the insurance coverage increases, the rotation length increases as well. No forest insurance contract worldwide proposes to insure drought-induced risk of forest dieback, and this short literature review highlights that no investigation is currently carried out in this area. Indeed, in Europe, forest insurance markets are focused only on storm and/or fire risks. Traditionally, insurance against drought risk was applied for agricultural sector through insurances based on meteorological index (Halcrow, 1948; Dandekar, 1977). This type of insurance seems to be relevant for forest sector as well.

Finally, risk management implies minimising the risk and generally comprises three major steps: risk analysis or risk assessment, risk handling, and risk control (Hanewinkel *et al.*, 2010). More specifically, the first step includes the calculation of the cost associated with potential damages (divided into risk identification and risk evaluation). The second step entails putting this calculation in relation with the management actions to be taken into account. The last step consists of the evaluation of the efficiency of the measures adopted to reduce the risks. While many studies evaluate the costs of damage (assessing risk probability and severity of damage) and provide prevention actions, only a few of them evaluate the effectiveness of adaptation strategies. Aditionally, Fouqueray and Frascaria-Lacoste (2020) highlighted that mitigation and adaptation studies underuse social sciences in forest research, and that social sciences can complement experimental sciences in climate studies led by forest researchers. This thesis is undoubtedly a step in this direction.

Description of the chapters

The thesis is composed of four chapters, which are presented in Table 1.

Table 1: Overview of the thesis organization.

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<tr><td colspan="5">Chapter IV</td></tr>
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The objective of the first three chapters was to test and compare different management-based strategies as potential adaptation means for reducing drought-induced risk of forest dieback from an economic perspective. The economic costs and benefits of management-based adaptation strategies were analysed from a private forest owner's perspective (financial balance), while considering the impact of these strategic decisions on carbon storage (carbon balance). The analysis was based on two case studies involving beech species in France. Indeed, beech is one of the most widespread species in France, and repeated drought events are expected to cause a decline in beech productivity in the near future (Charru *et al.*, 2010). In terms of methods, several forest-growth models were combined with an economic approach. The outputs of forest-growth models served as inputs for the economic approach. The forest-growth models allowed for the simulation of forest growth as well as aboveground and belowground carbon balance. While often neglected, soil carbon accounts for more than half of the forest's carbon stock (Dupouey and Pignard, 2001). In order to account for climate change uncertainty, two different scenarios were considered, namely the representative concentration pathways (RCP) 4.5 (*i.e.,* the most optimistic scenario) and 8.5 (*i.e.,* the most pessimistic scenario) (IPCC, 2013). Losses due to drought-induced risk of forest dieback were examined from a strictly financial standpoint and in terms of carbon sequestration. Different adaptation strategies were compared and combined. The three chapters differed in the tested adaptation strategies, the forest-growth models used, the economic evaluation performed, and the way the economic value of carbon sequestration was assessed.

The **first chapter** focuses on the case study of beech forests in the Burgundy region. Burgundy is a highly afforested French region, where deciduous forests have suffered from many diebacks in recent years. During stand turnovers, forest owners have gradually replaced native species with more productive and valuable species such as Douglas-fir and adopted a more dynamic silviculture as a means to compensate for future climate change damage, avoid financial losses, and respond to a growing demand for timber (Da Ronch *et al.*, 2016). However, other adaptation strategies exist and can be considered. To this aim, two incremental adaptation strategies, reduction of rotation length and reduction of the initial stand density, were tested with the substitution of beech by Douglas-fir (transformational adaptation). Two levels of drought risk were considered based on two levels of soil water capacity: intermediate and low. A process-based forest-growth model, known as CASTANEA, was combined with a traditional forest economic approach through LEV. CASTANEA is a mechanistic model for simulating the functioning of the principal managed European tree species (Davi *et al.*, 2005; Dufrêne *et al.*, 2005). The model simulates the main stocks of the forest ecosystem (*i.e.*, carbon, water, and nitrogen) both aboveground and belowground. It integrates the risk of mortality related to water stress (Davi and Cailleret, 2017) and takes the specificity of each species into account. The outputs of CASTANEA (*i.e.*, timber production and carbon sequestration) were used to provide an economic comparison of the adaptation strategies under study. The economic analysis was conducted using both the Faustmann model and the Hartman model. Faustmann's LEV takes the costs and the benefits from timber harvesting into account, whereas Hartman's LEV also considers the benefits from amenities, in our case carbon sequestration. Benefits from carbon sequestration were computed using the social cost of carbon. The maximization of LEVs showed that adaptation provided the best economic return, as opposed to the baseline or the "do-nothing" scenario. Combining strategies appeared as a relevant way to adapt forests in view of a drought-induced risk of forest dieback. Indeed, substitution with Douglas-fir combined with a reduced initial density and a reduction of the rotation length (*i.e.,* the combination of the three adaptation strategies considered) was the best strategy under both levels of drought risk and both climate scenarios. From an economic standpoint, the combination of different strategies was therefore more beneficial for the forest owner than each strategy separately (synergy *vs.* additionality). Finally, beneficial scenarios from an ecological perspective were not necessarily beneficial in economic terms and *vice versa*. In this chapter, CASTANEA model was used for the first time for the purpose of forest management. Although it worked well, the architecture of the CASTANEA model did not make it possible to compute intraspecific (uneven-aged forests) and interspecific (mixture of species) mixed stands.

In the **second chapter**, MATHILDE, a distance-independent individual-based model, was used to study diversification, a transitional adaptation, as a potential adaptation strategy to drought-induced risk of forest dieback. The second chapter focuses on the case study of beech forests in the Grand-Est region, which is another highly afforested French region. Beech and oak species are frequently co-occurring species, and mixed forests of beech and oak are common in Europe (Pretzsch *et al.*, 2013). Moreover, oak is more drought-tolerant than beech (Scharnweber *et al.*, 2011) and can increase drought resistance and resilience of beech due to interspecific facilitation (Zapater *et al.*, 2011). Two types of diversification were tested: mixture of beech species with oak species (under different proportions of mixture) and mixture of different tree diameter classes (*i.e.,* uneven-aged forests), which has never been analysed as a potential adaptation strategy. MATHILDE was combined with a traditional forest economics approach using LEV. MATHILDE is a tree-level model for simulating both even-aged and uneven-aged managed stands as well as pure and mixed stands of beech and sessile oak in Northern France (Fortin and Manso, 2016). The model was implemented in the CAPSIS platform (Dufour-Kowalski *et al.*, 2012), which contains a carbon accounting tool (CAT, Pichancourt *et al.*, 2018). CAT allows for the representation of complex emission life cycles inherent to managed forests. Simulations were performed under different recurrences of drought events that are a consequence of climate change. The outputs from MATHILDE (timber production) and CAT (carbon sequestration) were used to provide an economic comparison of the adaptation strategies. MATHILDE is designed to simulate forest growth in a stochastic manner using the Monte Carlo technique. Both Faustmann's and Hartman's criteria, suitable for deterministic settings, have been adapted to the stochastic framework: The development of the so-called double-weighted LEV allowed for the approximation of expected LEVs. The analysis of the impact of adaptation decisions on carbon sequestration was developed by considering three different carbon-accounting methods (*i.e.,* market value, shadow price, and social cost of carbon). The maximisation of the double-weighted LEV criterion led to the identification of the best adaptation strategies from an economic perspective. The results showed that while diversification reduces the loss in timber volume due to drought-induced risk of forest dieback and increases LEV, it also reduces carbon storage. Therefore, trade-offs between the financial balance and the carbon balance need to be considered. With regard to timber production (*i.e.*, volume harvested) and economic value (LEV), a combination of different strategies can be more beneficial to the forest owner than each strategy separately (*i.e.,* synergistic effects)

The two first chapters focused on drought-induced risk, although forest stands can be affected by several hazards during the same rotation. Indeed, in France, drought and windstorm are the two main damaging abiotic risks (Rouault *et al.*, 2006; Bonnesoeur *et al.*, 2013). Therefore, in the **third chapter**, the cumulative impact of both drought- and windstorm-induced risks was investigated. This is the first study investigating these two risks simultaneously, having independent recurrences, from an economic standpoint. This analysis was based on the case study (beech forests in Grand-Est) and methods (MATHILDE and CAT simulations to compute the double-weighted LEV and three accounting methods of carbon) already used in the second chapter. The same adaptation strategies were considered as well, since diversification can also be suitable to cope with windstorm damage (Mason and Valinger, 2013). Simulations were performed under different recurrences of drought and/or windstorm risks. The general results were identical considering drought and/or windstorm risks: Diversification increases timber production and LEV, but reduces carbon storage. The two risks as well as the adaptation strategies showed some synergies in terms of timber production and economic value (LEV).

However, the maximisation of the double-weighted LEV criterion showed that considering both risks affects the conclusions and recommendations compared to investigating each risk separately: The best scenario depended on the climate scenario, the risk(s), the discount rate, and the carbon price considered. Finally, the results showed that trade-offs between the financial balance and the carbon balance (*i.e.,* adaptation *vs.* mitigation) are possible.

The first three chapters focused on forest adaptation through the change of silvicultural practices (*i.e.,* management-based adaptation), comparing different strategies at the regional scale. Another way to help forest owners cope with drought-induced risk of forest diebacks is through the development of forest insurance contract (*i.e.*, market-based adaptation). Insurance is also part of soft adaptation strategies (World Bank, 2010). Therefore, the last and **fourth chapter** proposes to extend index-based insurance policies to the coverage of economic losses due to drought-induced risk of forest dieback at the national scale. The effectiveness of insurance contracts in smoothing income fluctuations was studied by simulating annual productivity levels of two species commonly found in French forests, *i.e.*, beech and oak. Simulations were performed using CASTANEA, fed with the reference climate (1960-2015) from the SAFRAN reanalysis system (Vidal *et al.*, 2010). Different indices with differentiated complexity levels were tested and compared. These include simple indices based on cumulative rainfall such as the standardized precipitation index (SPI) as well as more complex ones based on water stress such as the soil water stress index (SWS) (Guillemot *et al.*, 2017). Simulations were performed to calibrate various insurance contracts. Insurance schemes were optimized and tested. The results showed that while the optimal insurance contracts yield low gain on certainty equivalent income (CEI) and high basis risk (*i.e.,* lack of correlation between income and index realisation) they compensate for a significant part of the losses. The best contract was not proportional to the complexity of the index. Finally, our preliminary results did not show any clear advantage of differentiating insurance contracts based on tree species. Results highlighting the various perspectives of this first approach are discussed at the end of this chapter.

The above-described chapters provide a first economic approach of forest adaptation to drought-induced risk of dieback, developed in more details as following.

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Chapter I

An economic comparison of adaptation strategies towards a drought-induced risk of forest dieback

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Abstract

Drought is a source of stress that affects forest growth, resulting in financial losses for forest owners and amenity losses for society. Due to climate change, such natural events will be more frequent and intense in the future. In this context, the objective of this paper is to compare, from an economic perspective, different forest adaptation strategies towards a drought-induced risk of dieback. For that purpose, we focused on a case study of a beech forest in Burgundy (France) and we studied several adaptation options: density reduction, reduction of the rotation length, and substitution with Douglas-fir. We also considered two levels of drought risk (intermediate and low soil water capacity) and two climate scenarios from the IPCC (RCP 4.5 and RCP 8.5). We combined a process-based forest-growth simulator (CASTANEA) with a traditional forest economics approach. The results showed that adaptation provided the best economic return in most of the scenarios considered. Combining strategies appears as a relevant way to adapt forests in view of a drought-induced risk of forest dieback. We also demonstrated the importance of considering two disciplinary fields. Beneficial scenarios in an ecological perspective were not necessarily beneficial in an economic one and *vice versa*.

Keywords: Forest; Drought; Adaptation; Climate change; Economics; Risk; Carbon; CASTANEA.

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1. Introduction

Drought is the principal source of stress that limits forest health (Zierl, 2004), even if drought-induced impacts on forest health have been underestimated for a very long time due to inconspicuous damage at first sight (Spiecker, 2003). A drought occurrence translates into economic and social losses. Indeed, forests play a role in wood production but also offer many ecosystem services such as carbon storage, preservation from soil erosion and biodiversity. In parallel, drought-induced tree dieback is significantly increasing worldwide (Bréda and Badeau, 2008), even more with climate change that is increasing the frequency, duration and intensity of extreme events (Dale *et al.*, 2001).

Human interventions also affect drought through silviculture. Indeed, sustainable forest management is needed to maintain the resilience of forest ecosystems and to cope with climate threats such as drought (Bréda and Badeau, 2008). In fact, forest owners can protect their forests through adaptation and several strategies seem to be well suited for adapting forests to increasing risks of drought. Some examples of these measures include the reduction of rotation length or stand density, as well as shifting to species better-adapted to drought (Spittlehouse and Stewart, 2003).

In this context, we can therefore ask ourselves what the relevant adaptation options are, from an economic perspective, to deal with the drought-induced risk of forest dieback. We thus propose an analysis of the economic costs and benefits of adaptation for forest owners to the drought-induced risk of dieback.

In the literature, few studies have tackled the question of adaptation to climate change using a forest economics approach. Such studies have typically performed a cost-benefit analysis through the maximization of the net present value (NPV) or Faustmann's land expectation value (LEV). In this context, several strategies are then analysed. Hanewinkel *et al.* (2010) and Brunette *et al.* (2014) studied the shift to better-adapted species. The first paper deals with a shift from Norway spruce to European beech in Germany, while the second one deals with a change from Norway spruce to Douglas-fir in France. Whereas in Germany adaptation seems to correspond to financial loss, in France it seems that conversion to Douglas-fir may be a source of profit for the forest owner. The species mixture is analysed in Yousefpour and Hanewinkel (2014) with the question of admixing beech into a Norway spruce stand. They found that the best solution in economic terms is to establish beech regeneration in 46% of the Norway spruce area. Bréda and Brunette (2019) focused on the reduction of rotation length for Douglas-fir in France as a potential adaptation strategy towards a drought-induced risk of forest dieback. They showed that adaptation is always preferable in economic terms for the forest owner.

This short literature review reveals that past articles always focused on one strategy at a time. They never compared different strategies or analysed combinations of them. An exception is probably the study by Jönsson *et al.* (2015), which compares different adaptation strategies against storms. However, the methodology is different and based on the impact of adaptive forest management on productivity and sensitivity to storms. Another observation is that only one article deals with the drought-induced risk of forest dieback (Bréda and Brunette, 2019). Finally, climate scenarios are rarely considered.

The objective of this paper is to carry out an economic comparison of different adaptation strategies to fight against the drought-induced risk of forest dieback. For that purpose, we adopted an original approach that combines CASTANEA, a process-based forest-growth model, with a classical forest economic analysis. CASTANEA is a mechanistic model for simulating the functioning of the main managed European tree species (Davi *et al.*, 2005; Dufrêne *et al.*, 2005). The model simulates the main stocks of the forest ecosystem (carbon, water, nitrogen) aboveground and belowground, at time steps ranging from half an hour to a century. Only a mechanistic model can precisely simulate forest growth in reaction to drought and climate change, as well as the impact in terms of carbon sequestration. CASTANEA was chosen because it is the only model that simulates both carbon sequestration (Davi *et al.*, 2006) and tree growth (Davi *et al.*, 2009), while integrating the risk of mortality related to water stress (Davi and Cailleret, 2017) and that takes the specificity of each species into account, contrary to global models. We simulated forest stands according to different adaptation strategies (density reduction, reduction of rotation length and species shift) under two climate scenarios from the IPCC (RCP 4.5 and 8.5) and for two levels of drought risk related to a variation in soil water capacity (intermediate and high). We then used the outputs of CASTANEA to provide an economic comparison of the adaptation strategies. We performed a classical forest economics analysis based on Faustmann's formula and Hartman's formula. Faustmann's LEV takes the costs and the benefits from wood harvesting into account, whereas Hartman's LEV also considers the benefits from amenities, in our case, carbon sequestration. The maximization of these criteria showed that adaptation provided the best economic return, as opposed to the baseline or the “do-nothing” scenario. Indeed, substitution with Douglas-fir combined with a reduced initial density and a reduction of the rotation length was the best strategy under both levels of drought risk and both climate scenarios. From an economic perspective, the combination of different strategies was therefore more beneficial for the forest owner than each strategy separately (synergy *vs*. additionality).

These results are discussed with regard to the financial balance and the carbon balance. The rest of the paper is structured as follows. The material and the methods are presented in Section 2. Section 3 provides the results. The results are discussed in Section 4, and Section 5 concludes.

2. Material and methods

2.1. Some definitions

2.1.1. Characterization of drought and risk

According to the IPCC (2002), drought is defined as “a phenomenon that occurs when precipitation is significantly below normal recorded levels and that causes significant hydrological imbalances that are detrimental to systems of land resources production”. More precisely, from the ecophysiological point of view, drought is a reduction of the soil water reserve sufficiently severe to prevent the optimal functioning of trees due to insufficient precipitation, high temperature and large water uptake by trees. The definitions of drought vary greatly from country to country, but the literature identifies four different types of drought, including the edaphic (or agronomic) drought that is particularly of interest to us since it refers to the soil and to the impacts on living beings.

The precipitation regime is the first determinant in the development of a state of drought. It results from a pluviometric drought, which is a prolonged rainfall deficit compared to the mean or median (that is the normal state). However, drought also depends on the evapotranspiration level that is closely related to the temperature and atmospheric drought. The estimation of the water balance makes it possible to define the conditions under which precipitation distribution, soil water reserves and losses by evapotranspiration or drainage induce a negative effect on trees, referred to as water stress. According to Lebourgeois *et al.* (2005), water stress is the most important concept for the forest manager since water is the determinant of good stand health. We use the available water content (AWC) to illustrate this water stress.

According to Crichton (1999), drought risk can be described in terms of three components: the hazard, the stand exposure to the hazard and the stand's vulnerability. The hazard is characterized by its intensity (*i.e.*, the magnitude of the phenomenon), its severity (linked to the duration of the phenomenon), and its frequency (*i.e.*, the probability of damage). Exposure is the level or the conditions at which the stand may be in contact with the hazard. It is a function of the geographical location and the physical context, which can limit or accentuate the hazard (*e.g.*, compact and shallow soils). Vulnerability refers to the internal characteristics of the stand, influenced by species ecology, soil characteristics or stand density. It shows the extent to which the stand is likely to suffer from damage related to the hazard. Consequently, it takes the sensitivity of individuals to the effects of a hazard into account, as well as their ability to resist, adapt to them, and to return to the baseline situation (*i.e.*, resilience) (UNEO, 2007). A hazard (which is only a natural process) becomes a natural risk only when there is an interaction between the hazard and the population, goods and activities affected (Veyret *et al.*, 2013). The natural risk therefore implies the perception of this hazard by the population and, subsequently, its management (for cohabitation with the danger) (Veyret *et al.*, 2013). Adaptation strategies will consequently play a role on vulnerability through the implementation of a water-saving silviculture.

The impacts of drought may be classified as biological or socioeconomic. Four categories of biological impacts can be distinguished: accommodation through changes in physiological functioning (Bréda and Badeau, 2008; Matesanz and Valladares, 2014), in phenology or in tree growth (Solberg, 2004; Matesanz and Valladares, 2014); genetic adaptation (de Miguel *et al.*, 2012); and migration and tree mortality (Spiecker *et al.*, 2004; Galiano *et al.*, 2011; Galiano *et al.*, 2012). The biological impacts begin at the tree level, which result in impacts at the stand level, which, in turn, result in impacts at the ecosystem level. Thus, at the stand level, loss of growth proportional to drought intensity induces loss of productivity, whereas at the ecosystem level, drought reduces most of the biological cycles that affect the functions of the forest and that lead to a loss of ecosystem services, mainly wood production and carbon sequestration (Maroschek *et al.*, 2009). In terms of socio-economic impacts, drought generates financial losses linked to the current value of felled timber resulting from the loss of marketability, a decrease in future stand value, the additional cost of forest restoration, and the loss of hunting and other regular income (Birot and Gollier, 2001). Additionally, drought is also linked to the loss of carbon sequestration, which generates financial and social losses, as well as the loss of other amenities such as recreation (Thürig *et al.*, 2005).

These impacts are likely to be intensified in the near future due to climate change. Indeed, climate change is a global phenomenon due to an anthropogenic cause: the increase in the atmospheric concentration of greenhouse gases, the most important of which is carbon dioxide (CO_2) (IPCC, 2013). Climate will thus evolve towards an increase in average temperature, an escalation in the differences between wet and dry regions, a decrease in water availability, and an increase in the frequency and the intensity of extreme events such as severe drought (Spiecker, 2003). However, increasing CO_2 can also limit the drought effect by increasing the water use efficiency of plants (Davi *et al.*, 2006; Keenan *et al.*, 2013).

2.1.2. Adaptation strategies

In order to try to limit the increasing impacts of drought, several adaptation strategies can be identified. We chose to test two main adaptation strategies according to their importance in the literature and according to the classification of soft and hard adaptation strategies[4] given by the World Bank (2010): (i) the reduction of rotation length (soft adaptation); and (ii) species substitution from beech to Douglas-fir (hard adaptation). These two strategies are analysed separately as well as jointly, and in combination with a third strategy, density reduction (soft adaptation).

First, the reduction of rotation length reduces the time of exposure to a drought event and the vulnerability of trees due to aging (Spiecker, 2003; Bréda and Peiffer, 2014). Young and old trees are the most vulnerable to drought (Archaux and Wolters, 2006): Special attention must therefore be paid to the establishment of young trees and to avoiding long rotations.

Second, the introduction of drought-tolerant species and provenances reduces the aerial carbon balance, while using the same forest area (FAO, 2011; Keskitalo and Carina, 2011). Moreover, it would be preferable to introduce so-called transitional species or varieties, *i.e.*, species able to thrive in both the current and projected future climate (*e.g.*, pine, Douglas-fir, *Robinia*).

Third, the reduction of the leaf area and, therefore, of the stand density, improves the resistance of forest stands to the lack of water (Archaux and Wolters, 2006; Bréda and Badeau, 2008), reduces the intensity and duration of water deficits, and increases water availability (Spiecker, 2003). This results in an increase in initial planting space (Spiecker, 2003) and more intensive and earlier thinning (Spiecker, 2003; Keskitalo and Carina, 2011) in order to stabilize and thus protect stands (*i.e.*, to have a continuous forest cover and to protect it from all hazards) (Spiecker, 2003; Bernier and Schoene, 2009), to take advantage of CO_2 fertilization to maximize and accelerate growth (Bernier and Schoene, 2009), to increase resistance and resilience to future damage (Kerhoulas *et al.*, 2013), and to stimulate the growth of trees remaining after a drought (Kerhoulas *et al.*, 2013).

2.2. Case study

2.2.1. Case study area: Burgundy region

Burgundy is a rural region and one of the major forest regions in France in terms of afforestation (30% afforestation rate), which has increased over the last 30 years. It has a great geographic (from valleys to mountains) and geological diversity. Its contrasted climate is of the Atlantic type

[4] Soft adaptation consists of measures that are desirable, even in the absence of climate change, with soft and progressive change, while hard adaptation implies greater and more brutal changes to adapt the ecosystem.

with rainfall spread out throughout the year, ranging from 600 mm (Loire valley) to 1500–1800 mm (Morvan peaks), average temperatures between 9.5 and 11.5°C, events of snow and frost, as well as frequent late frosts in May. However, biotic (pests and pathogens such as canker and bark beetle) and abiotic factors (*e.g.*, late frosts, repeated water deficits, soil compaction due to forest mechanization) threaten the health of forests. Burgundy forests are characterized by private property (68% according to IGN, the French National Forest Inventory), a primary function of production, and a dominance of deciduous trees except in the Morvan. Indeed, beech and oak represent 90% of the forest areas. However, these two species are sensitive to summer water deficit and many beech diebacks can be observed, which may be amplified by a weakly dynamic silviculture. This is why, during the turnover of Burgundy stands, deciduous forests gradually shift to forests with more productive and valuable species such as Douglas-fir in order to anticipate future climate changes and to thus avoid financial losses, and to respond to the growing demand for wood, with a more dynamic silviculture. Beech and Douglas-fir also produce commercially highly-valued wood in Burgundy, *i.e.*, their annual production is 221,000 m^3 and 898,000 m^3, respectively, in private forests.

2.2.2. Species of interest

Beech (*Fagus sylvatica* L.) is a natural species representing 15% of the forest production area in France. It is a typical shade-tolerant species, requiring a certain degree of atmospheric humidity and sufficient soil moisture (Latte *et al.*, 2015), which can barely tolerate extreme conditions, as well as spring frosts (Godreau, 1992). More precisely, it is the climate criteria (annual distribution of precipitation and temperature) that determine the presence or the state of health of beech, rather than soil conditions (Godreau, 1992). However, due to climate change, this species could decline or even disappear (Charru *et al.*, 2010). Indeed, the increase in the frequency and intensity of spring droughts and heat waves has already negatively affected the annual growth of beech trees (Latte *et al.*, 2015). Damage can lead to the death of beech when the proportion of dead aerial biomass exceeds a threshold of 58% (*i.e.*, percentage of foliar deficit reached) (Chakraborty *et al.*, 2017). This mortality is directly related to the availability of water and light resources, as well as to the increase in neighboring interactions and in the diversity of tree species (Chakraborty *et al.*, 2017).

Overall, distribution in France is limited by temperature for Mediterranean species and by water supply for northern species as well as deciduous species (beech, oak) and conifers (Douglas-fir, spruce, fir). This is why the hydric constraints in the northern half of France cast doubts on the existence and the production of these latter species, particularly beech that has had many diebacks on superficial soils with low water reserves. Substitution with a species that is more productive under a dry climate and more valuable, such as Douglas-fir, seems to be a better economic solution, as suggested by Latte *et al.* (2015) for the regeneration of old beech stands. In addition to this, with the interest of the French public authorities (*e.g.*, the National Forest Fund in France during the period 1946–2000) and some professionals (builders, wood producers, furniture industries) in the rapid growth, the lower cost of production and maintenance, and the standardized sawing techniques of conifers (pine, fir), the demand would be based on an accelerated national production of conifers. Since two-thirds of the French forest is composed of deciduous trees, the transition could be backed by a less water-consuming silvicultural system, which is linked to the subject of our study.

A native of western North America, Douglas-fir (*Pseudotsuga menziesii* Mirb.) is an introduced species valued by forest managers for its rapid growth and the quality of its wood (Da Ronch *et al*., 2016). It appears to be able to provide significant wood production under a relatively dry climate (Eilman and Rigling, 2012; Da Ronch *et al*., 2016). However, despite all these qualities, Douglas-fir is more sensitive to high temperatures due to its high leaf area (*i.e*., strong transpiration) than to droughts. This explains the damage reported in France after the drought in 2003 (because of its combination with a heat wave), in particular in the Burgundy region (Sergent *et al*., 2014). Moreover, although Douglas-fir is described by some authors as a drought-resistant species (Eilman and Rigling, 2012), it does not seem to be well-adapted to the range and accumulation of intense and recurrent episodes of drought after a severe one, which could be explained by a lack of resilience, *e.g*., after the drought in 2003 (Sergent *et al*., 2014).

Beech and Douglas-fir are both mesophilous species, *i.e*., species that grow in habitats that are neither extremely dry nor extremely humid (ONF, 1999). They prefer mountainous areas due to their high requirement for atmospheric moisture, although they are present in the plains. They are therefore sensitive to heat. Douglas-fir and beech have the same skewed and moderately deep rooting, but with different transpiration control during drought (ONF, 1999). Indeed, beech has a higher midday soil water potential and, consequently, a higher sensitivity to drought compared to Douglas-fir (ONF, 1999; Pierangelo and Dumas, 2012). Additionally, deciduous trees have a higher demand for available water content than conifers (ONF, 1999): Beech therefore consumes more water reserves than Douglas-fir in summer. However, edaphic drought can be aggravated by the existence of a high evaporation demand. Finally, Bréda and Badeau (2008) confirmed that the development of beech is dependent on water balance and drought, whereas for species such as Douglas-fir, its development is mainly related to temperature, supporting our suggestion to substitute beech with Douglas-fir.

2.2.3. Study scenarios

For this study, we chose to test two levels of drought risk defined according to the level of soil available water capacity (AWC). Three levels of AWC were considered: 150, 100 and 50 mm. These levels were chosen according to the range of AWC of current beech stands in Burgundy. The level of 150 mm represents optimal water conditions for beech growth, 100 mm is the initial risky scenario with one-third less of the baseline level of water availability for trees, and 50 mm is the second risky scenario in which the water availability is below 40% of the baseline. This threshold of 40% of the maximum AWC represents the conditions under which beech starts to regulate water consumption and thus has difficulties to grow and survive (Lebourgeois *et al*., 2005).

With respect to the uncertainty of future climate, the consequences of the two extreme climate scenarios from the IPCC were analysed: RCP 4.5 and RCP 8.5 (IPCC, 2013). RCP 4.5 represents the most optimistic scenario, and RCP 8.5 represents the most pessimistic one (higher temperature, higher CO_2 concentration, *etc*.). All of these elements result in [(2 baselines + 7 scenarios × 2 drought risks) × 2 climates], which is equal to 32 scenarios. The two baselines and the seven scenarios are summarized in Table I.1. The scenario is indicated by the following code for the benchmark (AWC of 150 mm): Baseline_Species (B for beech or D for Douglas-fir).

The scenario is indicated by the following code for both levels of drought risk (AWC of 100 mm and 50 mm): Species (B for beech or D for Douglas-fir)_Silviculture (NA for no adaptation, DR for density/rotation reduction and S for substitution). Scenarios for beech were composed of a classical path (Baseline_B and B_NA) and three dynamic ones (B_DR1, B_DR2 and B_DR3) representing the silviculture of the density/rotation reduction strategy. Simulations for Douglas-fir were composed of a classical path (Baseline_D and D_S) representing the silviculture of the substitution strategy plus two dynamic ones (D_S+DR1 and D_S+DR2) in order to test the combination of the two strategies.

Table I.1: The different scenarios considered and their distinctive code.

Code	Scenario
Baseline_B	Benchmark, current beech stand
Baseline_D	Benchmark, Douglas-fir in current conditions
B_NA	Beech stand without adaptation
B_DR1	Beech stand with a reduced rotation length
B_DR2	Beech stand with an initial reduced initial density and rotation length
B_DR3	Beech stand with a second reduced initial density and rotation length
D_S	Douglas-fir stand (substitution of beech)
D_S+DR1	Douglas-fir stand (substitution of beech) combined with a reduced rotation length
D_S+DR2	Douglas-fir stand (substitution of beech) combined with a reduced initial density and rotation length

2.3. Methods

To compare the adaptation options to deal with the drought-induced risk of forest dieback, we first simulated forest growth with different silvicultural treatments according to these different adaptation strategies, the three different levels of water content and the two climate scenarios. The simulations were run with the CASTANEA model. The economic approach was then applied to the outcome of the simulations.

2.3.1. Simulation of forest growth and silvicultural treatments

CASTANEA requires three different files as inputs: the inventory file, the species file and the weather file. First, the inventory file contains all the trees with their characteristics related to the simulated stand. R software makes it possible to generate the list of all the trees according to soil characteristics. The soil characteristics (height, stone content, *etc.*) are directly linked to the AWC and parameters of the managed stand (tree diameter, LAI, *etc.*). Second, the species file contains all the species-specific parameters that control the energy budget, growth (photosynthesis, respiration), carbon allocation and water consumption (see Table I.B1 in Supplementary Material). Third, the weather file contains the climatic characteristics of the studied site (global radiation, air temperature, relative air humidity, wind speed, precipitation). These georeferenced data for current and future climates (RCP 4.5 and RCP 8.5) came from the Météo France network for four different SAFRAN points of 8×8 km (3202, 3710, 4303, 5121), chosen to represent the variety of climates in Burgundy. All of the results for each scenario are then taken from the average of the four SAFRAN points (see Figure I.B1 in Supplementary Material).

CASTANEA simulates photosynthesis and respiration to estimate net primary production. Carbon is then allocated to six compartments following the allocation rules described in Davi *et al.* (2009) and Davi and Cailleret (2017): large roots, fine roots, reserves, leaves, branches and trunks. Biomass growth in the trunk is converted into volume growth from the density of the wood at the end of the year. This makes it possible to estimate growth in ring width and volume on an annual basis.

Table I.2: Characteristics of the different silvicultural paths used for beech and Douglas-fir: initial stand density (number of trees per hectare), regeneration mode (natural regeneration NR or plantation P), number of thinnings and rotation length (years) (source: CRPF).

Scenario	Initial stand density (trees/ha)	Regeneration mode (NR or P)	Number of thinnings	Rotation length (years)
Baseline_B and B_NA	5000	NR	9	95
B_DR1	5000	NR	7	80
B_DR2	3000	NR	7	80
B_DR3	1000	P	6	80
Baseline_D and D_S	1300	P	6	55
D_S+DR1	1660	P	3	45
D_S+DR2	660	P	3	45

The annual output data were the volume of wood, the mortality rate, and the carbon sequestrated into the forest stand. Risk of mortality by carbon starvation and hydraulic failure was assessed according to Davi and Cailleret (2017). For this purpose, we simulated non-structural carbohydrates ([NSC]) and midday leaf water potential. Hydraulic failure is computed when the midday leaf water potential drops below the P50 of the species (leaf water potentials below which 50% of conductivity loss occurs). The threshold of mortality on [NSC] is estimated by fitting the threshold to minimize the difference among simulated and measured annual mortality rates between 2000 and 2015 once the hydraulics failure was computed. The mortality measurements were taken from the French National Inventory on Burgundy.

The CASTANEA model simulated the forest growth of a stand of 1 ha through different silvicultural paths starting from a 125-year-old beech forest in Burgundy from 2000 to 2100. The silvicultural paths arise from the CRPF (Regional Center for Privately-Owned Forests) of Burgundy for both species. Table I.2 presents the different characteristics of each silvicultural path.

The seven silvicultural paths were simulated through three different AWC (50, 100 and 150 mm) that characterized the drought effect and two different IPCC scenarios (RCP 4.5 and RCP 8.5) that characterized the climate effect.

2.3.2. Economic approach

Figure I.1 illustrates, for one given IPCC scenario, the structure of the applied methodology from the simulation of forest growth to economic results. The resulting volume of wood for each scenario (outputs of the CASTANEA model) was the input of the economic approach.

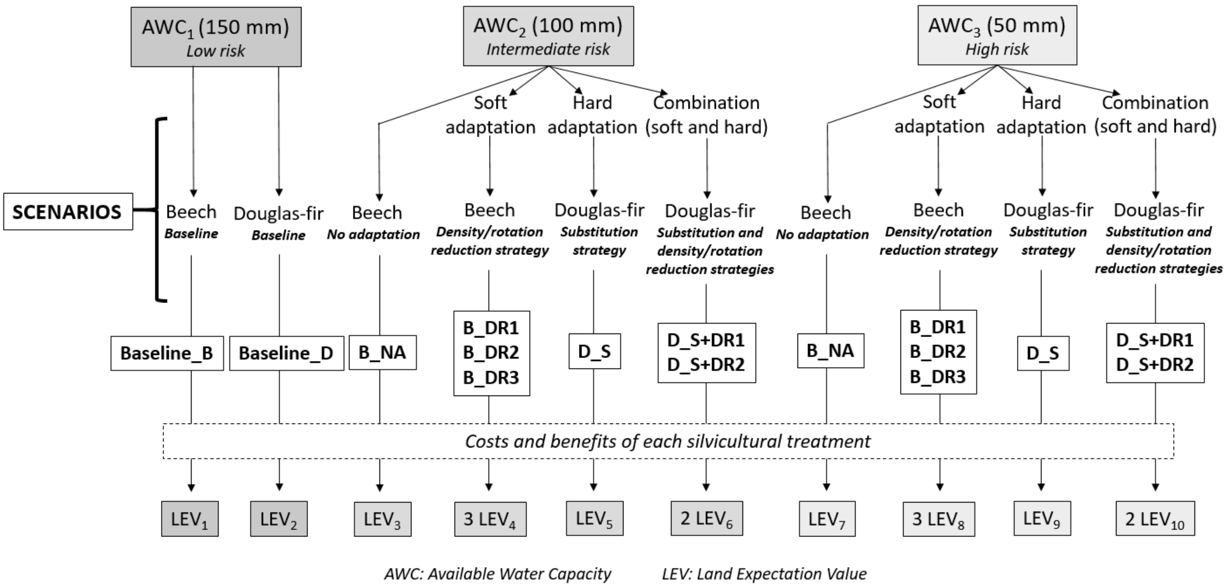

Figure I.1: Schematic representation of the methodology applied: From scenario structure to economic evaluation.

Our objective was to compare the 32 LEVs among scenarios. All the comparisons of LEV are detailed according to Figure I.1 as follows (taking only one IPCC scenario into account):

- (LEV 1 with LEV 3) and (LEV 1 with LEV 7): effect of drought.
- (LEV 3 with LEV 4) and (LEV 7 with LEV 8): effect of density/rotation reduction strategy.
- (LEV 1 with LEV 2) and (LEV 3 with LEV 5) and (LEV 7 with LEV 9): effect of species substitution strategy.
- (LEV 3 with LEV 6) and (LEV 7 with LEV 10): effect of species substitution strategy combined with that of density/rotation reduction.

First, the sum of an infinite number of rotations made it possible to calculate the land expectation value, commonly referred to as the Faustmann criterion in forest economics (Faustmann, 1849), as follows:

$$LEV\ (Faustmann) = \sum_{i=0}^{\infty}\sum_{n=0}^{N-1}\frac{B_n - C_n}{(1+r)^{(i.N+n)}} \tag{1}$$

where B is the benefits, C the costs, r the discount rate, n the stand age, N the rotation length and i the rotation number.

It is assumed here that the forest owner has a single objective: to maximize LEV. The infinite horizon used by this criterion makes it possible to compare management options associated with different temporal horizons, assuming that the silvicultural path was identical for each subsequent rotation after the first one. In other words, each silvicultural operation (thinning, maintenance, harvest) was implemented at the same age and for the same cost or benefit an infinite number of times. This may be seen as a limit of this criterion. However, other existing ones present greater limitations and are rarely adopted (Fraysse *et al.*, 1990; Morel and Terreaux, 1995). Faustmann's LEV takes the costs and the benefits from wood harvesting into account. After discussion with forestry experts, a discount rate r of 3% was chosen. A sensitivity analysis on this parameter was performed and is presented in Section 4.3.

We also asked ourselves if the consideration of forest ecosystem services may impact the economic results. In the context of mitigation of climate change, we chose to consider carbon sequestration in particular. In fact, carbon loss is rarely considered in the literature in addition to economic loss (see Yousefpour and Hanewinkel (2014) for an exception).

For that purpose, we also calculated Hartman's LEV, which makes it possible to consider the benefits from wood harvesting and from amenities simultaneously (Hartman, 1976), in our case, carbon sequestration[5].

The Hartman model was applied as follows:

$$LEV\ (Hartman) = \sum_{i=0}^{\infty}\sum_{n=0}^{N-1}\frac{B_n - C_n}{(1+r)^{(i.N+n)}} + \sum_{i=0}^{\infty}\sum_{n=0}^{N-1}\frac{B'_n}{(1+r)^{(i.N+n)}} \tag{2}$$

where B is the benefits from wood production, C the costs of the silvicultural treatment, B' the benefits from carbon sequestration provided by the forest stand, r the discount rate, n the stand age, N the rotation length and i the rotation number.

The discount rate r was also 3% for beech and Douglas-fir in order to be able to compare LEVs. To compute the benefits from carbon sequestration, we considered the additional sequestration of the standing wood and we chose the social cost of carbon of 44 EUR/T (Watkiss and Downing, 2008). The social cost of carbon is "an estimate of the total cost of damages generated by each ton of CO_2 that is spewed into the air" (Howard and Sterner, 2014). It therefore gives the total value of avoided damage caused by the flow of carbon to the atmosphere in the case of potential total deforestation.

[5] See Couture and Reynaud (2011) for a short review of studies using Hartman's framework with carbon storage.

Table I.3: Stand density (number of trees per hectare), volume of wood (in cubic meters per hectare) and associated net benefits from its production (in euros per hectare) for each silvicultural operation for the beech benchmark (Baseline_B).

Baseline_B		RCP 4.5		RCP 8.5	
Operations (tree age)	Stand density (N/ha)	Volume of wood (m^3/ha)	Net benefits (EUR/ha)	Volume of wood (m^3/ha)	Net benefits (EUR/ha)
Maintenance (5)	5000	24	-595	24	-595
Thinning 1 (15)	3000	106	-665	107	-665
Thinning 2 (30)	1500	170	852	168	841
Thinning 3 (35)	757	113	560	118	584
Thinning 4 (41)	523	104	483	111	514
Thinning 5 (49)	361	142	661	150	696
Thinning 6 (57)	249	168	1042	172	1067
Thinning 7 (65)	172	186	1437	185	1426
Thinning 8 (75)	119	210	2130	208	2114
Thinning 9 (85)	82	224	2781	219	2723
Harvest (95)		250	12524	249	12457

An example of silvicultural operations with associated net benefits from wood production is given in Table I.3 for the benchmark. The tables for the other scenarios are presented in the Appendices.

3. Results

3.1. Forest growth and mortality

Figures I.2 and I.3 show the results of the simulations of the forest stand per scenario and per RCP, in terms of growth (volume increment of wood in cubic meters per hectare) and mortality (in percentage terms), respectively. Mortality was taken into account when computing volume.

In Figure I.2, we can see that Douglas-fir has the highest mortality rate compared to beech and thus the baseline (Baseline_B). Adaptation does not affect mortality. There is no difference between scenarios when considering the same tree species. Climate change has a negative effect on mortality: Scenarios in RCP 8.5 (pessimistic climate scenario) present higher mortality rates than in RCP 4.5 (optimistic climate scenario). Regarding drought, in RCP 4.5, both levels of drought risk present the same pattern. In RCP 8.5, the high risk emphasizes the mortality of Douglas-fir.

In Figure I.3, we can see that Douglas-fir presents a higher volume increment of wood than beech (baseline and scenarios). Drought has a negative effect for all the scenarios: We observe a lower growth in scenarios with high risk as opposed to those with intermediate risk. Climate change has a negative effect for all the scenarios too: They present lower growth in RCP 8.5 than in RCP 4.5. Combinations of different strategies (D_S+DR1 and D_S+DR2) have the best growth, unlike non-adaptation (B_NA), which is below the baseline.

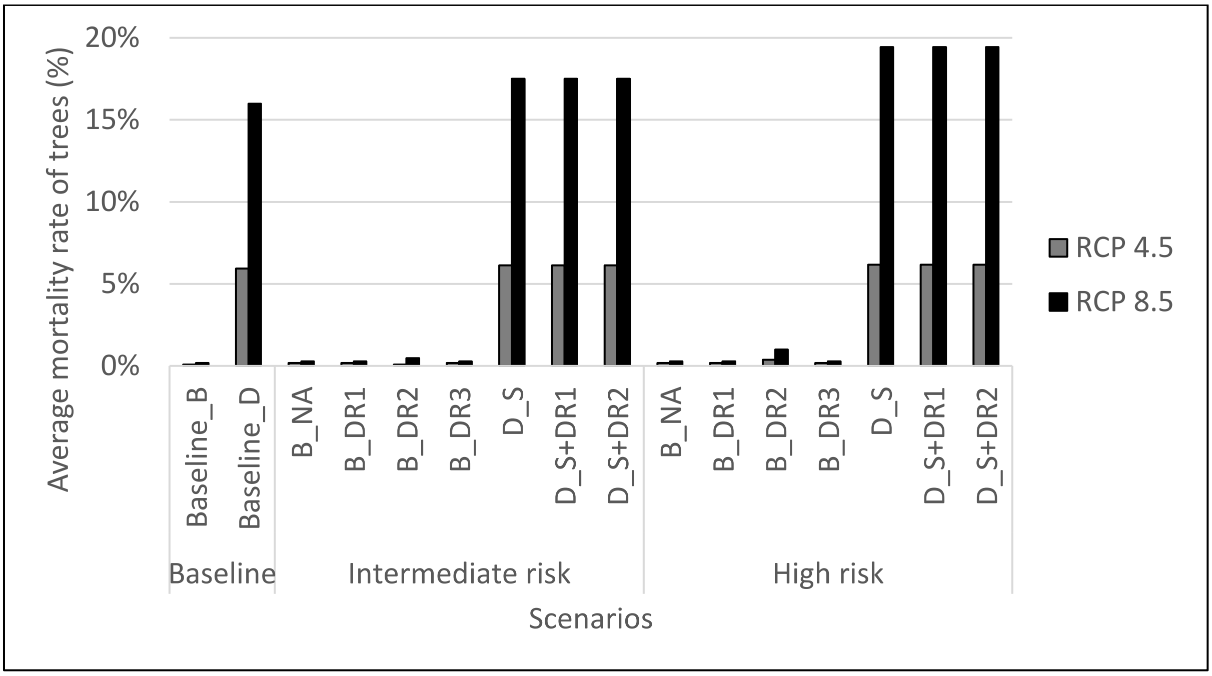

Figure I.2: Histogram representing the average mortality rate of trees (in percentage terms) for each scenario, for RCP 4.5 (gray) and RCP 8.5 (black).

These two figures presented interesting results from an ecological point of view. First, the scenarios with Douglas-fir showed the highest volume increment of wood, whereas they had the highest mortality rates. More precisely, the two scenarios that combined two strategies (D_S+DR1 and D_S+DR2) were the best ones, showing a higher growth in the more severe climate scenario (RCP 8.5) than in the small-temperature increment scenario (RCP 4.5). All these elements corroborate the literature describing Douglas-fir as a high productive species in dry climates (Eilman and Rigling, 2012; Da Ronch *et al.*, 2016).

In contrast, the scenarios with beech showed the lowest volume increment of wood, whereas they had the lowest mortality rate. More precisely, they showed a lower growth rate under the high drought risk than under the intermediate one, which is consistent with its known sensitivity to drought (Charru *et al.*, 2010; Latte *et al.*, 2015; Chakraborty *et al.*, 2017).

These two points demonstrate different sensitivities to drought and climate change. Indeed, beech reacts and is thus more sensitive to drought (precipitation effect) than to climate (temperature effect) (Latte *et al.*, 2015; Chakraborty *et al.*, 2017), and the contrary for Douglas-fir (Sergent *et al.*, 2014).

Generally speaking, drought negatively influences mortality and the volume increment of wood. Concerning climate change, the higher the intensity is, the more the mortality rate of the stand will increase. That is why, regarding these two outputs of the CASTANEA model, adaptation seemed more profitable than the baseline or the absence of adaptation.

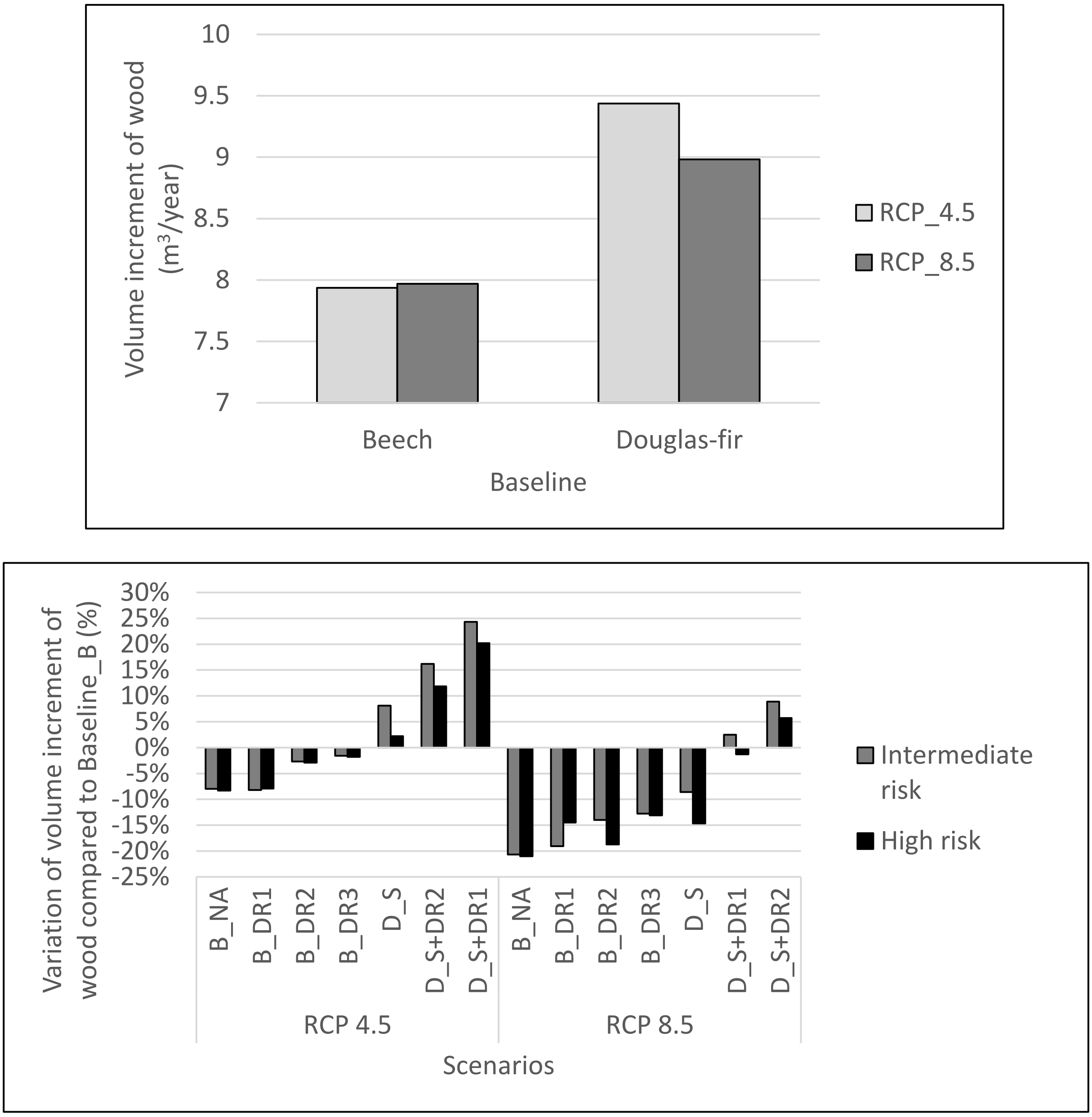

Figure I.3: Histograms representing the volume increment of wood (cubic meters per year) of the baselines (beech and Douglas-fir) (up) and the variation (in percentage terms) of each scenario compared to the beech baseline (down) for intermediate and high drought risks in RCP 4.5 and RCP 8.5.

3.2. Economic comparison

The resulting variations in LEVs compared to the baseline of beech (Baseline_B) are presented in Table I.4. Faustmann's LEV ranges from −983 to 4916 EUR/ha and from −866 to 4717 EUR/ha for the RCP 4.5 and 8.5, respectively. In terms of implementation of adaptation strategies, scenarios with a positive variation of LEVs compared to the baseline represent the benefit of adaptation for forest owners: B_DR1, B_DR2 and D_S+DR2. In contrast, scenarios with a negative variation of LEVs compared to the baseline represent the potential cost of adaptation for forest owners: B_DR3, D_S and D_S+DR1.

Concerning the baseline, maintaining the current beech stand was more profitable than substituting it with Douglas-fir. Table I.4 reveals that a substitution strategy combined with that of a density reduction (D_S+DR2) provides the best economic return, regardless of the level of drought risk and the climate scenario. In a second step, the density reduction of beech then provides the best economic return with the scenario B_DR2, followed by the scenario B_DR1. Note that the two other scenarios with Douglas-fir (D_S and D_S+DR1) are the worst options from an economic perspective, regardless of the level of drought risk and the climate scenario.

Table I.4: Variation of Faustmann's LEV (in percentage terms) of each scenario compared to the baseline of beech, for RCP 4.5 and RCP 8.5.

Scenario		RCP 4.5	RCP 8.5
Baseline	Beech	1555 EUR/ha	1572 EUR/ha
	Douglas-fir	-29%	-45%
Intermediate risk	B_NA	-13%	-14%
	B_DR1	79%	80%
	B_DR2	82%	82%
	B_DR3	-3%	-2%
	D_S	-67%	-80%
	D_S+DR1	-111%	-108%
	D_S+DR2	216%	200%
High risk	B_NA	-35%	-36%
	B_DR1	55%	55%
	B_DR2	57%	56%
	B_DR3	-27%	-26%
	D_S	-123%	-137%
	D_S+DR1	-163%	-155%
	D_S+DR2	167%	154%

Based on Table I.4, we can say that costs and benefits of adaptation strategies are clearly not additive, but synergies between adaptation strategies appear to be. For example, for an intermediate level of risk, considering only the reduction of the initial rotation length of the beech stand (B_DR1) allows a financial benefit (+79%), applying a first reduction of initial density (B_DR2) as well (+82%). However, a more intense density reduction (B_DR3) generates loss (−3%) due to the beech characteristics (shadow species). The same comment applied for high risk. In the same vein, implementing substitution alone (D_S) corresponds to financial loss (−67%), and adding a reduction of rotation length (D_S+DR1) increases the previous loss (−111%). However, combining the three strategies (substitution with a reduction of rotation length and stand density, D_S+DR2) makes it possible to generate the highest benefits (+216%). This observation is also true for high risk. Following these observations, it appears that the reduction of rotation length and density reduction are complementary.

3.3. Carbon sequestration

Figure I.4 shows the results of the simulations of the forest stand per scenario and per RCP, in terms of carbon sequestration (in grams of carbon per square meter of leaf per year).

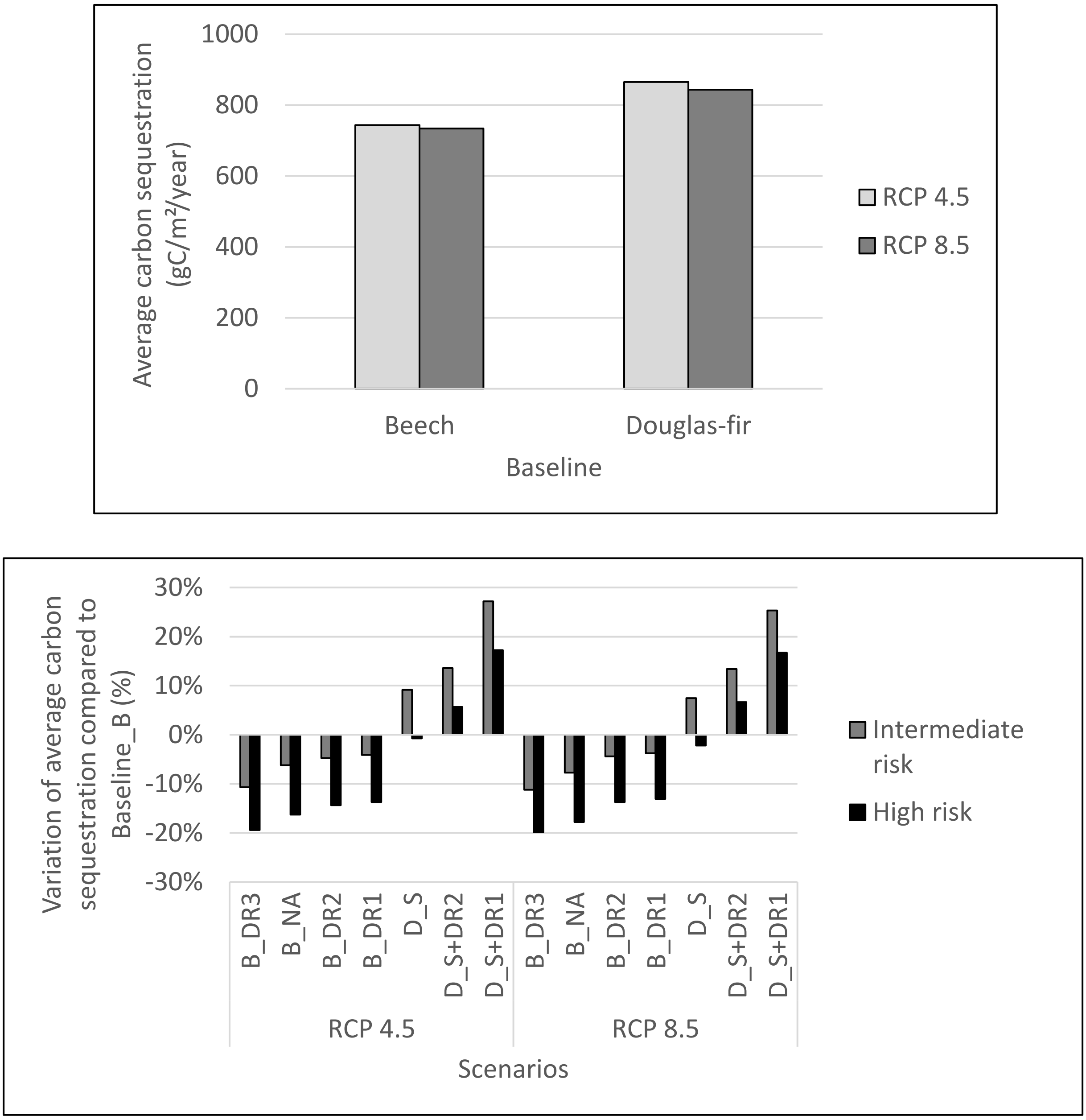

Figure I.4: Histograms representing the average carbon sequestration (in grams of carbon per square meter of leaf per year) of the baselines (beech and Douglas-fir) (up) and the variation (in percentage terms) of each scenario compared to the baseline of beech (down) for intermediate and high drought risks in RCP 4.5 and RCP 8.5.

Recall that mortality was considered in the computation of the volume. We can see that Douglas-fir presents a higher carbon sequestration than beech (baseline and scenarios). Drought has a negative effect for all the scenarios. They present lower carbon sequestration under a high risk than under an intermediate risk. Climate does not affect carbon sequestration (baseline and scenarios). Considering only beech, carbon sequestration decreases with the reduction of stand density (5000, 3000 and 1000 trees/ha for B_DR1, B_DR2 and B_DR3, respectively). Scenario D_S+DR1 that combines different strategies has the best carbon sequestration, in contrast to scenario B_DR3 (reduced density and rotation length), which is the worst one and below the baseline.

In economic terms, the resulting variations in LEVs compared to the baseline of beech (Baseline_B) are presented in Table I.5. The range of Hartman's LEV is from −230 to 5672 EUR/ha and from −969 to 5378 EUR/ha for the RCP 4.5 and 8.5, respectively. The same results are observed when considering Hartman's LEV: The scenario D_S+DR2 provides the best economic return, regardless of the climate and the level of drought risk.

Table I.5: Variation of Hartman's LEV (in percentage terms) of each scenario compared to the baseline of beech, for RCP 4.5 and RCP 8.5.

Scenario		RCP 4.5	RCP 8.5
Baseline	Beech	2789 EUR/ha	2829 EUR/ha
	Douglas-fir	-27%	-39%
Intermediate risk	B_NA	-11%	-12%
	B_DR1	37%	37%
	B_DR2	40%	40%
	B_DR3	-18%	-17%
	D_S	-51%	-62%
	D_S+DR1	-75%	-77%
	D_S+DR2	103%	90%
High risk	B_NA	-29%	-134%
	B_DR1	19%	19%
	B_DR2	21%	21%
	B_DR3	-35%	-34%
	D_S	-87%	-98%
	D_S+DR1	-108%	-107%
	D_S+DR2	72%	62%

4. Discussion

4.1. Adaptation from an economic perspective

From an economic point of view, our results suggest that adaptation may be relevant (Tables I.4 and I.5), and is consistent with the ecological point of view detailed in Section 3.1. More precisely, the substitution of beech with Douglas-fir combined with a reduced initial density and rotation length (D_S+DR2) provided the best economic return. Indeed, Douglas-fir wood is more valuable than that of beech because its wood has a natural durability that does not require chemical treatment to be used in outdoor construction. In contrast, beech is mainly used as firewood. Hotyat (1999) described its wood as having a low value and not being competitive compared to conifer wood due to its low durability, its red heart and its hydrophilic character. That is also why Latte *et al.* (2015) promoted substitution with Douglas-fir and, as of now, for the regeneration of old stands of beech.

However, two economic results were unexpected. First, despite its low quality and - as a result - value, the reduced initial density and rotation length scenario B_DR2 provides the second best return. Indeed, while Douglas-fir can be more interesting (as described above), beech is the natural species of this region. This implies that the regeneration of a beech stand was natural (seeds from old trees) and thus without costs, unlike that of a Douglas-fir stand which is obtained artificially (plantation) involving plantation costs. Forest owners may perceive these high plantation costs (compared to the natural regeneration of beech) as a brake to adaptation. It may be interesting then to encourage them to shift to better-adapted tree species. A way to incite them to choose adaptation may be the subsidization of plantation by the public authorities. Indeed, in a context of international negotiation to limit climate change, forests have to play a role and public authorities have an interest in adapting them. In France, forests are privately owned, so incentives to encourage owners to adapt, such as subsidization, may be required. On the other hand, the forest sector should adapt to these silvicultural changes and it is likely that the government may also have a role to play.

Second, while the scenarios D_S+DR1 and D_S+DR2 were the best ones in terms of growth (from an ecological point of view), they presented contrasted economic results. Indeed, scenario D_S+DR2 provides the best economic return, and scenario D_S+DR1 the worst one. This coincides with the objective of scenario D_S+DR2 that was to reduce plantation costs by starting with 660 trees/ha (instead of 1660 trees/ha for the other scenario as a way to meet industrial demand). This result also proves the importance of having an interdisciplinary vision. Bringing together the two fields leads to the emergence of a consensual and more relevant solution, scenario D_S+DR2. Additionally, in terms of wood quality, the implementation of scenario D_S+DR2 is only possible with a “deciduous filler”. In our case, it would be an addition of beech (which regenerates naturally) at the understorey to avoid branched Douglas-fir and to thus obtain good quality wood. This beech filler can also offer additional benefits such as the production of firewood.

Whether we consider scenario D_S+DR2 or scenario B_DR2, they both showed the success of combining different strategies. This agrees with the idea of Jönsson *et al.* (2015), who promote a portfolio of adaptation strategies to reduce the risk of damage. This result also supports the recommendation of the World Bank (2010) to combine soft and hard adaptation. This idea to combine strategies should be more widespread among forest owners. Indeed, adaptive management is part of the category of “no regret” or “win-win” strategies: Reducing stand density makes it possible to save water in the soil in both scenarios and money as well in scenario D_S+DR2 under (or not) a drought risk. However, the lack of relevant information is seen as a brake to adaptation (Yousefpour and Hanewinkel, 2015; Sousa-Silva *et al.*, 2016). Forest owners are reluctant to adapt due to a large uncertainty concerning the impact of the implemented adaptation strategies. In this sense, the combination of strategies offers flexibility to the owners in addition to adaptive capacity. The reduction of the rotation length increases the flexibility of forest management, thus reducing the decision horizon, particularly in scenario D_S+DR2, which has the shortest rotation length.

In general, drought had a greater impact on LEV than the climate: The higher the drought intensity was, the more the LEV decreased.

4.2. Carbon consideration

Figure I.4 showed that when considering scenarios of beech and those of Douglas-fir separately, the higher the initial stand density, the greater the amount of carbon sequestered. This does not coincide with drought adaptation strategies. That is why the combination of two strategies through the best scenario (D_S+DR2) is a good trade-off between adaptation and mitigation of climate change.

Hartman's LEV gives the highest values compared to Faustmann's LEV. Without taking carbon sequestration into account, we underestimate the value of the forest stand. However, Hartman's LEVs present the most extreme values and, consequently, the greatest variation of values in the most severe climate scenario (RCP 8.5). This criterion therefore takes all of the externalities of carbon sequestration linked to the implied silviculture into account. These results prove the importance of considering carbon sequestration, mainly in the context of climate change, and not just wood production to compute the profitability.

This approach leads to an initial consideration of carbon in these analyses. Many debates exist around carbon accounting. That is why this step can be developed in further studies. Indeed, it would be interesting to know how positive externalities from carbon sequestration can be managed in reality. Amenities can generate carbon credits, which can result in a payment to forest owners for the total sequestered carbon or the annual increment of sequestered carbon of the past year (Dwivedi *et al.*, 2012). Any payment scheme has to be carefully plan (Guitart and Rodriguez, 2010) whether compensation is made at the final harvest or as continuous source of revenue every year. We can take the future use of wood products with different lifetimes into account, as well as the carbon stored in these products. This suggests that wood quality has to be integrated into our study. For example, firewood directly re-emits sequestered carbon, whereas carbon in a wooden table has a longer lifetime. With this approach in mind, the individual negative effect of the wood production of forest owners should be considered at the same time as the economic consequences for society, along with the social contribution through different wood products.

Finally, on the whole, adaptation makes society, as well as the economy, more resilient to hazards (Konkin and Hopkins, 2009), which refers to the “forests for adaptation” of Locatelli *et al.* (2010). However, the implementation of effective adaptation measures depends on the availability of human resources and skills (Maroschek *et al.*, 2009). Adaptive management is part of the “no regret”, reversible and nontechnical strategies and the ones that reduce the decision horizon due to its flexibility with respect to the evolution of climate change and its beneficial investments, even in the absence of drought risk (Courbaud *et al.*, 2010). Adaptive management is thus part of the adaptation measures to climate change and also contributes to its mitigation by increasing the carbon-sink capacity, for example (Kolström *et al.*, 2011). FAO (2011) emphasizes that "effective management of global forests not only reduces the risk of damage from potential disasters, but also has the potential to mitigate and adapt to climate change".

4.3. Sensitivity analysis

Economic evaluation often includes a sensitivity analysis of discount rates to test the robustness of the computed LEVs. Consequently, we evaluated the variation of the different LEV functions of the discount rate for each scenario analysed. The results are presented in Figure I.5.

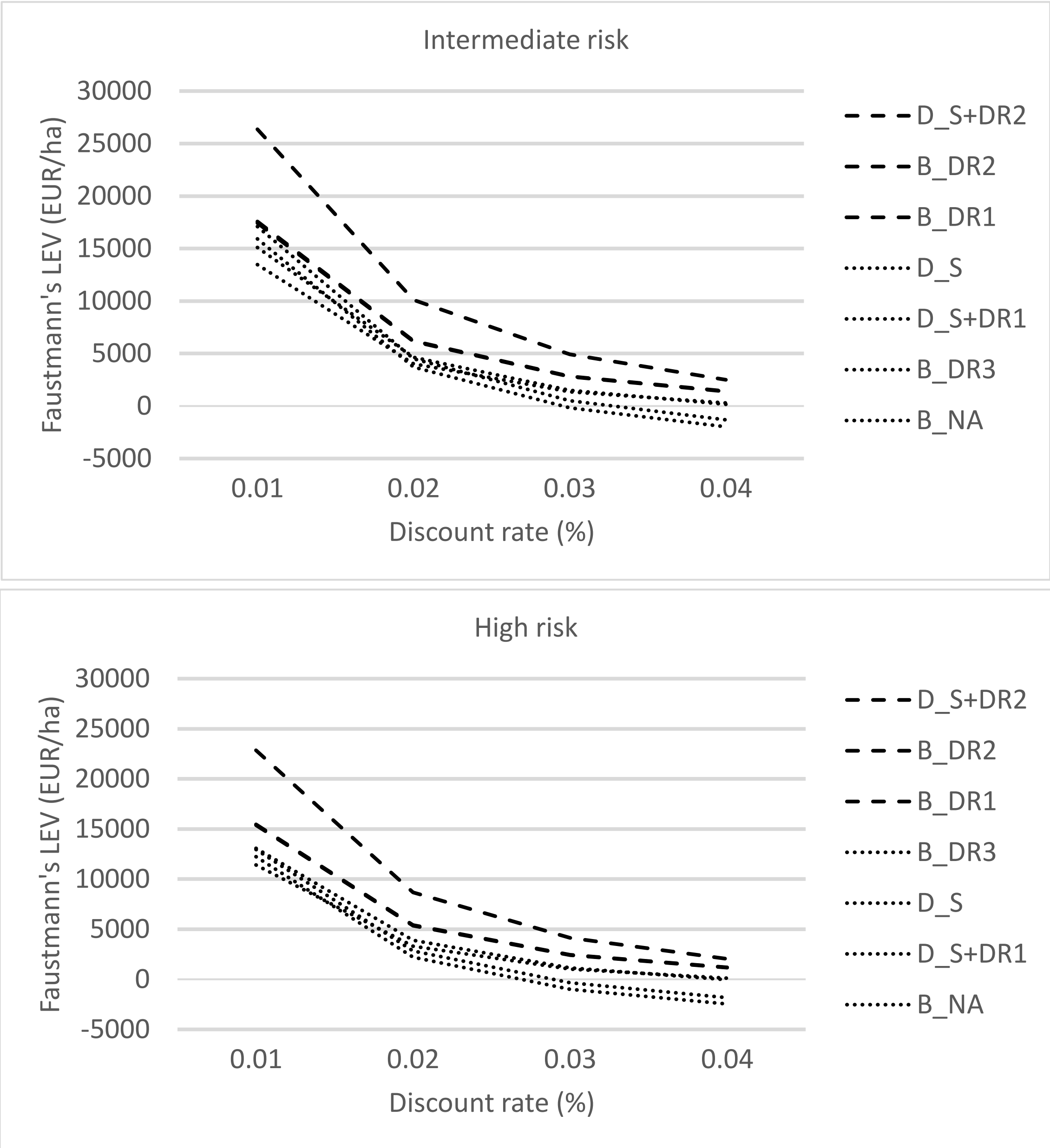

Figure I.5: Faustmann's LEV (EUR/ha) for each scenario as a function of the discount rate for RCP 4.5, for the intermediate risk (up) and the high risk (down).

In Figure I.5, Faustmann's LEV of scenario D_S+DR2 is the highest, regardless of the discount rate for both risks. The second one is scenario B_DR2 since the discount rate for an intermediate risk is 1.5%, regardless of the discount rate for the high one. The order between scenarios does not change since the discount rate is 3.5%.

The same results are observed considering the RCP 8.5 and Hartman's LEV. All these elements demonstrate the robustness of our results.

4.4. Limits and perspectives

The CASTANEA model was used for the first time for the purpose of forest management. A good reaction of volume increment was observed after a thinning, *i.e.*, a boost of growth because of the increase in growing space and water resources in the first years. However, drought generates effects on growth for the year of the event and for one or more years after (Power *et al.*, 1995; Rouault *et al.*, 2006). These post-drought effects are taken into account in the model through the effect of non-structural carbon on growth, but they are still not properly evaluated. Three adaptation strategies (density/rotation reduction and species substitution) were chosen as the most relevant and mentioned in the literature, but also on the basis of their technical feasibility with the CASTANEA model and in Burgundy. Indeed, substitution of beech stands with Douglas-fir has already been tested in the Morvan. The architecture of the CASTANEA model (inventory file for one species growing at the same age) did not make it possible to compute intraspecific (uneven-aged forests) and interspecific (mixture of species) stands, which explains why this well-documented measure was not studied here. Indeed, many studies have proved the effectiveness of mixed stands in terms of biodiversity objectives to reduce drought risk (FAO, 2011; Keskitalo and Carina, 2011). Mixtures make it possible to diversify wood production instead of opposing the different uses, with, in general, conifers providing lumber wood and deciduous trees providing energy wood. Therefore, to investigate this strategy, we need to more extensively study mixed stands and the (aboveground and underground) interactions between species (competition and symbiosis) in order to be able to model them. Nonetheless, while all forest services must be taken into account in order to preserve the multifunctionality of forests, mixture strategy probably requires taking trade-offs between adaptation to drought and biodiversity objectives into account, which may be conflicting.

Another potential limitation of this study is that our model considers a fixed wood price grid depending on tree diameter. First, the wood price varies with the tree diameter but also fluctuates with the supply, which are two parameters affected by climate change (see Section 3.1), and such variations are not considered in our study. Second, the wood prices increase together with the diversity of wood uses and the substitution effect of fossil fuels. More and more uses are being discovered for Douglas-fir wood, and its growing demand is not considered in this paper.

5. Conclusion

The productivity of forests is severely limited by water availability in the soil. We observed that drought induces extensive tree dieback due to impacts over several years that result in high socio-economic losses, which will then be accentuated by climate change. Moreover, the literature describes the drought hazard at different levels, but without spatial analysis, as is the case for storms and especially fire hazard (monitoring, prevention by creating transects). Indeed, a mapping based on synthetic water deficit indices would be interesting to “spatialize” the estimation of available water reserves at any given time.

Our study shows that the adaptation of beech stands in Burgundy is needed to fight against drought-induced dieback. Adaptation is costly for forest owners. Therefore, in order to consider adaptation to drought in forest management, the forest owner needs to analyse exposure to drought, to assess potential impacts, and to evaluate the adaptive capacity of both the forest stand and the management system. In addition to this, an important question was how to select suitable measures from the multitude of adaptation options. On the basis of growth and carbon sequestration simulations by the CASTANEA model, substitution of beech stands with Douglas-fir, combined with a reduction of the initial stand density and a reduction of the rotation length, provides the best economic return, regardless of the climate and the level of drought risk. Our paper is the first to compare different adaptation strategies to face the drought-induced risk of forest dieback, and the synergy of both strategies provided a robust result. We also showed that adaptation is not always as economically beneficial as ecologically and, consequently, trade-offs between objectives may exist (Johnston and Withey, 2017).

When considering extreme events such as drought, forest management and its adaptation mainly depend on the given objectives (wood production, carbon sequestration), on the forest owner (government, territorial community or private), as well as on the type of stands (existing, to be created, to be reforested). Research in this field can improve our understanding of drought risk and its implied damage mechanisms. Therefore, to improve management options under severe drought, studies of this environmental hazard and risk should be pursued.

In the aim of promoting the best strategy to be combined with drought risk for decision-making, we showed the importance of the interconnection between different fields (ecology and economics), to take the multifunctionality of forests (wood production and carbon sequestration in this case), the need for general information about silvicultural treatments, and the collaboration between different sectors (forest managers and researchers) into account. Additionally, since drought increases vulnerability to secondary attacks (pests and pathogens), current challenges for disturbance modelling would include carrying out multiple-risk analyses in dynamic ecosystem models for decision support in forest management.

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Supplementary material

A. Silvicultural operations with associated net benefits from wood production and carbon sequestration for each scenario

B_NA		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations (tree age)	Density (N/ha)	Wood (m³/ha)	Benefits (EUR/ha)	Wood (m³/ha)	Benefits (EUR/ha)	Wood (m³/ha)	Benefits (EUR/ha)	Wood (m³/ha)	Benefits (EUR/ha)
Maint. (5)	5000	24	-595	23	-595	23	-595	22	-595
Thin. 1 (15)	3000	97	-665	83	-665	97	-665	83	-665
Thin. 2 (30)	1500	157	786	132	660	152	760	129	644
Thin. 3 (35)	757	102	506	85	422	107	530	92	455
Thin. 4 (41)	523	93	432	79	367	101	470	87	404
Thin. 5 (49)	361	128	594	108	503	136	633	115	534
Thin. 6 (57)	249	153	948	130	808	157	976	134	830
Thin. 7 (65)	172	172	1330	148	1142	170	1315	148	1141
Thin. 8 (75)	119	197	1998	174	1769	192	1951	167	1693
Thin. 9 (85)	82	209	2602	183	2281	202	2509	176	2194
Harv. (95)		232	11599	202	10094	230	11476	199	9936

B_DR1		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maint. (5)	5000	28	-61	27	-61	27	-61	26	-61
Thin. 1 (15)	1100	106	-705	94	-705	105	-705	91	-705
Thin. 2 (22)	500	83	452	74	404	79	429	68	372
Thin. 3 (31)	350	112	506	96	432	115	517	99	445
Thinning 4 (36)	200	118	1011	101	870	125	1068	110	946
Thin. 5 (44)	130	132	1156	116	1011	142	1241	125	1098
Thin. 6 (52)	70	154	2350	135	2055	160	2442	143	2178
Thin. 7 (60)	60	153	875	135	772	154	879	138	788
Harv. (80)		273	13666	246	12321	267	13368	239	11934

B_DR2		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maint. (5)	3000	25	-61	24	-61	24	-61	23	-61
Thin. 1 (15)	1000	104	-705	91	-705	105	-705	92	-705
Thin. 2 (22)	500	93	467	83	415	89	445	77	386
Thin. 3 (31)	350	120	539	102	459	121	546	104	466
Thin. 4 (36)	200	122	1047	104	896	128	1097	112	963
Thin. 5 (44)	130	134	1173	117	1022	143	1252	126	1099
Thin. 6 (52)	70	155	2366	135	2062	161	2462	143	2180
Thin. 7 (60)	60	153	878	135	772	154	883	137	786
Harv. (80)		273	13663	246	12284	266	13317	236	11819

B_DR3		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maint. (5)	1000	26	-1525	25	-1525	25	-1525	24	-1525
Thin. 1 (31)	500	197	984	171	853	196	978	169	846
Thin. 2 (36)	350	124	558	107	480	130	587	115	518
Thin. 3 (44)	200	144	1238	124	1068	155	1331	135	1160
Thin. 4 (52)	130	150	1311	129	1128	157	1374	138	1209
Thin. 5 (60)	70	165	2522	145	2209	167	2549	148	2266
Thin. 6 (70)	60	180	1029	162	928	175	1003	155	887
Harv. (80)		231	11535	208	10379	226	11321	201	10074

Baseline_D		RCP 4.5		RCP 8.5	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maintenance (5)	1300	29	-4310	24	-4310
Thinning 1 (25)	750	228	966	199	840
Thinning 2 (30)	520	175	1076	154	945
Thinning 3 (35)	360	160	1727	147	1583
Thinning 4 (40)	280	153	1361	144	1278
Thinning 5 (45)	230	166	1340	155	1253
Thinning 6 (50)	200	185	1204	172	1118
Harvest (55)		232	12734	236	12958

D_S		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maint. (5)	1300	27	-4310	25	-4310	22	-4310	20	-4310
Thin. 1 (25)	750	209	885	177	747	177	747	144	610
Thin. 2 (30)	520	159	979	133	820	138	846	114	699
Thin. 3 (35)	360	144	1552	121	1299	132	1422	111	1196
Thin. 4 (40)	280	138	1225	116	1031	130	1156	110	980
Thin. 5 (45)	230	150	1212	127	1025	141	1134	119	960
Thin. 6 (50)	200	168	1092	143	928	153	1014	129	841
Harv. (55)		211	11581	179	9865	216	11888	181	9972

D_S+DR1		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maint. (5)	1660	29	-5110	27	-5110	24	-5110	22	-5110
Thin. 1 (25)	800	242	1256	212	1099	207	1072	175	909
Thin. 2 (31)	560	171	1025	149	892	151	906	128	769
Thin. 3 (38)	430	180	1673	157	1460	171	1582	151	1398
Harv. (45)		226	12405	198	10896	239	13165	215	11828

D_S+D R2		RCP 4.5				RCP 8.5			
		Intermediate risk		High risk		Intermediate risk		High risk	
Operations (tree age)	Density (N/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)	Wood (m^3/ha)	Benefits (EUR/ha)
Maint. (5)	660	30	-1200	28	-1200	24	-1200	22	-1200
Thin. 1 (30)	520	282	1194	247	1046	241	1021	206	871
Thin. 2 (35)	360	253	2729	222	2390	223	2401	193	2082
Thin. 3 (40)	280	213	1891	188	1668	193	1711	168	1496
Harv. (45)		230	10359	204	9158	238	10724	214	9627

Baseline	Beech				Douglas-fir			
	RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5	
Tree age (years)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)
5	-85	-3734	-84	-3714	-78	-3451	-80	-3512
15	36	1574	36	1588				
25					77	3406	67	2961
30	22	966	21	919	-18	-793	-15	-667
35	-19	-852	-17	-749	-5	-225	-2	-106
40					-2	-102	-1	-44
41	-3	-135	-2	-105				
45					4	194	4	173
49	13	565	13	576				
50					6	281	6	246
55					16	691	22	948
57	9	388	8	336				
65	6	266	4	185				
75	8	352	8	349				
85	5	208	4	162				
95	9	402	10	451				

B_NA	RCP 4.5				RCP 8.5			
	Intermediate risk		High risk		Intermediate risk		High risk	
Tree age (years)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	Carbon (T/ha)	Benefits (EUR/ha)
5	-79	-3458	-68	-3009	-78	-3421	-67	-2962
15	33	1444	28	1235	33	1452	28	1235
30	20	898	17	733	19	815	16	685
35	-19	-818	-16	-697	-15	-671	-13	-551
41	-3	-136	-2	-93	-2	-85	-2	-71
49	12	515	10	432	12	519	9	416
57	9	376	8	332	7	318	6	280
65	7	287	6	260	4	189	5	207
75	8	364	9	391	7	325	6	282
85	4	188	3	138	3	145	3	146
95	8	340	6	276	9	414	8	333

B_DR1	RCP 4.5				RCP 8.5			
	Intermediate risk		High risk		Intermediate risk		High risk	
Tree age (years)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)
5	-93	-4074	-83	-3673	-91	-3986	-81	-3558
15	36	1577	32	1395	36	1563	31	1361
22	-8	-339	-7	-288	-9	-390	-8	-344
31	10	437	7	326	12	541	10	457
36	2	82	2	79	3	143	4	169
44	5	212	5	211	6	259	5	227
52	7	329	7	287	6	273	6	260
60	0	-17	0	3	-2	-98	-2	-77
80	41	1794	38	1661	39	1696	34	1505

B_DR2	RCP 4.5				RCP 8.5			
	Intermediate risk		High risk		Intermediate risk		High risk	
Tree age (years)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)
5	-93	-4073	-83	-3662	-90	-3970	-80	-3524
15	35	1547	31	1359	36	1562	31	1369
22	-4	-154	-3	-121	-5	-236	-5	-219
31	9	391	6	284	11	482	9	394
36	1	35	1	35	2	99	3	129
44	4	178	4	183	5	227	5	200
52	7	316	6	275	6	274	6	258
60	-1	-25	0	-3	-2	-106	-2	-82
80	41	1786	37	1650	38	1669	34	1475

B_DR3	RCP 4.5				RCP 8.5			
	Intermediate risk		High risk		Intermediate risk		High risk	
Tree age (years)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)
5	-78	-3439	-70	-3095	-77	-3375	-68	-3004
31	67	2935	58	2543	66	2917	57	2522
36	-25	-1086	-22	-953	-22	-974	-18	-807
44	7	302	6	265	8	370	7	301
52	2	82	2	67	1	27	1	43
60	5	233	5	237	3	152	4	153
70	5	215	6	258	3	121	2	96
80	17	759	15	677	17	762	16	692

D_S	RCP 4.5				RCP 8.5			
	Intermediate risk		High risk		Intermediate risk		High risk	
Tree age (years)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)
5	-71	-3139	-61	-2674	-73	-3222	-61	-2703
25	71	3121	60	2632	60	2633	49	2151
30	-17	-745	-15	-642	-13	-578	-10	-454
35	-5	-230	-4	-194	-2	-89	-1	-42
40	-2	-90	-1	-66	-1	-25	0	-9
45	4	186	4	167	4	158	3	131
50	6	263	5	231	5	227	3	150
55	14	634	12	545	20	896	18	775

D_S+DR1	RCP 4.5				RCP 8.5			
	Intermediate risk		High risk		Intermediate risk		High risk	
Tree age (years)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)
5	-76	-3362	-67	-2953	-81	-3568	-73	-3206
25	82	3614	72	3163	70	3084	59	2615
31	-24	-1067	-21	-946	-19	-832	-16	-705
38	3	141	3	129	7	290	8	336
45	15	674	14	607	23	1027	22	960

D_S+DR2	RCP 4.5				RCP 8.5			
	Intermediate risk		High risk		Intermediate risk		High risk	
Tree age (years)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)	C (T/ha)	Benefits (EUR/ha)
5	-78	-3422	-69	-3034	-81	-3553	-72	-3189
30	95	4199	84	3677	82	3590	70	3064
35	-10	-424	-8	-373	-6	-270	-4	-184
40	-14	-599	-11	-504	-10	-447	-8	-369
45	6	256	5	233	15	680	15	678

B. Supplementary data

Table I.B1: Parameters of CASTANEA model for Douglas based on the parametrization for Abies alba and literature survey.

Variable	Value	Unit
Leaf construction cost	1.21	$g_C.g_C^{-1}$
Coarse roots construction cost	1.2	$g_C.g_C^{-1}$
Fine roots construction cost	1.28	$g_C.g_C^{-1}$
Wood construction cost	1.18	$g_C.g_C^{-1}$
Rate of alive cells in stem	0.46	%
Rate of alive cells in branches	0.46	%
Rate of alive cells in coarse roots	0.46	%
[lignines] in roots	0.25	$g_{Lignines}.g_{DM}$
[lignines] in fine roots litter	0.38	$g_{Lignines}.g_{DM}$
[lignines] in leaf litter	0.38	$g_{Lignines}.g_{DM}$
[lignines] in fine branches litter	0.35	$g_{Lignines}.g_{DM}$
[lignines] in coarse branches litter	0.35	$g_{Lignines}.g_{DM}$
[lignines] in coarse roots litter	0.38	$g_{Lignines}.g_{DM}$
initial [NSC] in living tissue	0.15	$g_{Lignines}.g_{DM}$
[nitrogen] in leaves	0.017	$g_N.g_{DM}^{-1}$
[nitrogen] in coarse roots	0.00094	$g_N.g_{DM}^{-1}$
[nitrogen] in fine roots	0.0036	$g_N.g_{DM}^{-1}$
[nitrogen] in branches	0.01027	$g_N.g_{DM}^{-1}$
[nitrogen] in stem	0.00094	$g_N.g_{DM}^{-1}$
[nitrogen] in reserves	0.0004	$g_N.g_{DM}^{-1}$
Predawn potential for growth cessation	-1.6	Mpa
Carbon allocation coefficient to wood	0.42	$g_C.g_C^{-1}$
Fine roots turn over	1	$g_C.g_C^{-1}.year^{-1}$
Ratio between branches and total aboveground biomass	0.15	$g_C.g_C^{-1}$
Ratio between coarse roots and total wood biomass	0.20382166	$g_C.g_C^{-1}$
Ratio between fine roots and leaves biomass	0.3	$g_C.g_C^{-1}$
Branches mortality rate	0.00007	$g_C.g_C^{-1}.year^{-1}$
Needle area	0.0005	m2
Leaf Mass per Area of sun leaves	360	g/m2
Extinction coefficient of Leaf Mass per Area within the canopy	0.0729	m^{-2}
Leaf angle	40	°
Branches angle	8.7	°
Slope of the crown area to dbh relation	0.08151	m^2.cm-1
Intercept of the crown area to dbh relation	0.69535	m^2
Slope of the LAI-dbh relationship	1.5	$m^2.cm^{-1}$
Power coeffiecient of the LAI-dbh relationship	0.45	cm^{-1}
Power coeffiecient of the [NSC] effect on the LAI-dbh relationship	0.3	g_C^{-1}
Slope of the height-dbh relationship	1.52	m

Power coeffcient of the height-dbh relationship	0.7972	cm^{-1}
Form coeffcient of stem	0.447	$m^3.m^{-3}$
Wood density	550	$Kg.m^{-3}$
canopy clumping coefficient	0.46	$m^{-2}.m^{-2}$
Wood reflectance in PIR domain	0.3	$J.J^{-1}$
Wood reflectance in PAIR domain	0.15	$J.J^{-1}$
Leaf reflectance in PIR domain	0.33	$J.J^{-1}$
Leaf transmittance in PIR domain	0.225	$J.J^{-1}$
Leaf reflectance in PAR domain	0.09	$J.J^{-1}$
Leaf transmittance in PAR domain	0.045	$J.J^{-1}$
Water storage capacity per unit of leaf area	0.4	$mm.m^{-2}$
Water storage capacity per unit of bark area	0.32	$mm.m^{-2}$
Slope of the water interception coeficient	0.85	$mm.mm^{-1}$
Intercept of the water interception coeficient	1.5	mm
Ratio between stemflow and throughfall	0.35	$mm.mm^{-1}$
Intercept of ball and berry relation	0.001	$mmol.m^{-2}.s^{-1}$
Slope of ball and berry relation	9.5	Dimensionless
Roots to leaves resistance to flow transport per Area Sapwood basis	28747	$g_{H2O}.Mpa^{-1}.m^{-2}.s^{-1}.g_C^{-1}$
Capacitance of trunk	0.04	Kg/m3/Mpa
Water potential inducing 50% loss of conductivity	-3.6	Mpa
Dependency between VCmax and leaf nitrogen density	23.3210084	$mol_{CO2}.gN^{-1}.s^{-1}$
Curvature of the quantum response of the electron transport rate	0.7	Dimensionless
Base temperature for forcing budburst	1	°C
Base temperature for leaf growth	0	°C
Base temperature for forcing leaf fall	20	°C
Date of onset of rest	70	Julian day
Date of onset of ageing	213	Julian day
Critical value of state of forcing (from quiescence to active period)	400	°C
Critical value of state of forcing (from leaf development to maximum LAI)	350	°C
Critical value of state of forcing (from leaf development to leaf maturity)	424	°C
Critical value of state of forcing (from NStart2 to leaf fall period)	100	°C
Critical value of state of forcing from NStart2 to end of wood growth	300	°C
Minimal temperature below which frost has an effect on young buds	-3	°C
Phenologie type (1\: deciduous 2\: evergreen)	2	
Maximum needle or leaves lifespan	11	years

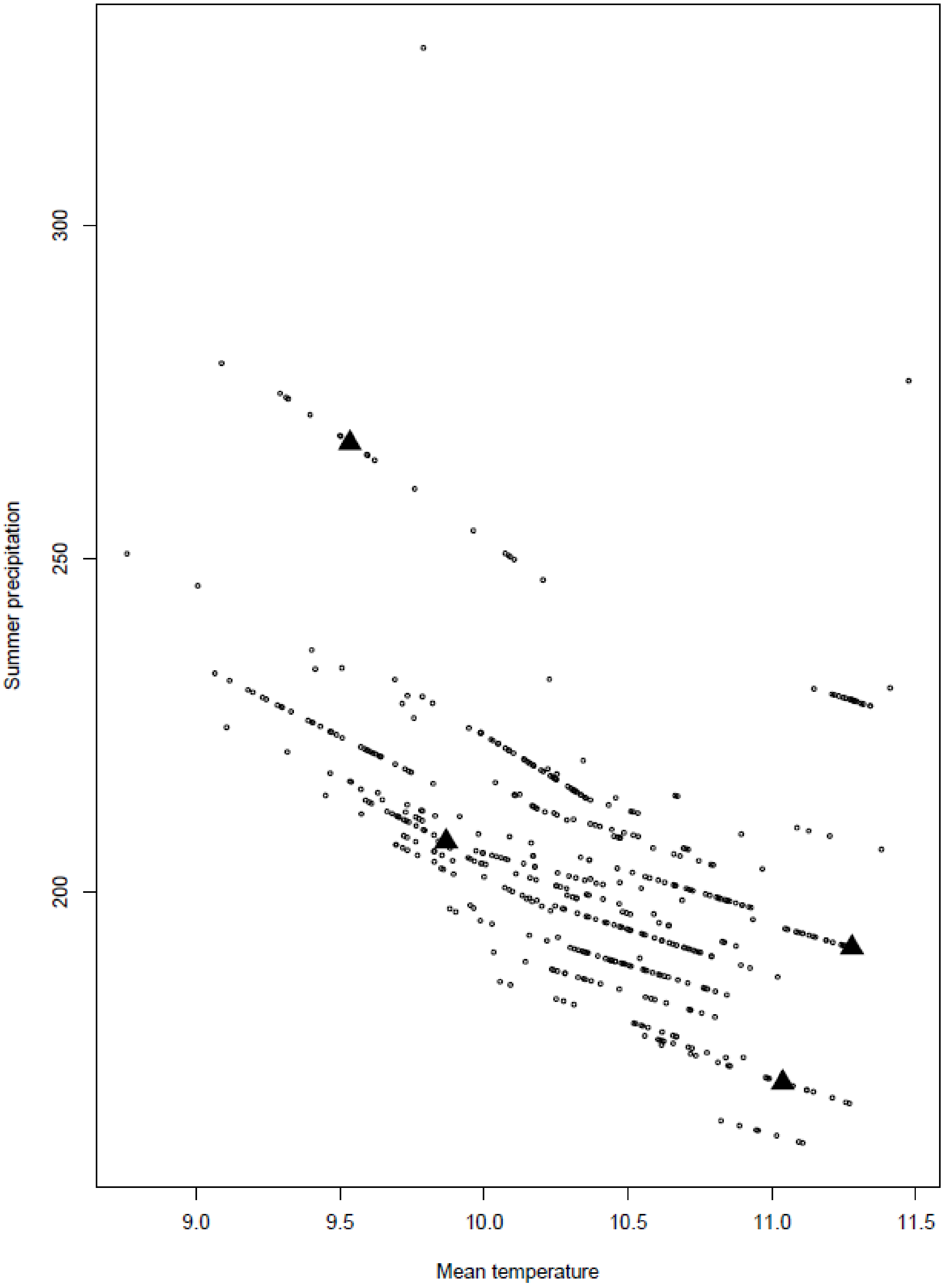

Figure I.B1: The four SAFRAN points (3202, 3710, 4303, 5121) function of the summer precipitation and mean temperature.

Chapter II

Is diversification a good option to reduce drought-induced risk of forest dieback? An economic approach focused on carbon accounting

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Abstract

Extreme or recurrent drought events are the principal source of stress impairing forest health. They cause financial losses for forest owners and amenity losses for the society at large. Most of the forested area in the Grand-Est region (France) is dominated by beech, which is projected to decline in the future due to repeated drought events driven by climate change. Beech forests need to adapt and diversification is a management option that has the potential to reduce drought-induced risk of dieback. We studied two types of diversification that were analysed separately and jointly: mixture of beech species with oak species and mixture of different tree diameter classes (*i.e.,* uneven-aged forest), which is rarely considered as an adaptation strategy. We also considered two types of loss (financial and carbon sequestration) under different recurrences of drought events, which are consequences of climate change. We combined a forest growth simulator (MATHILDE) with a frequently used economic approach (*i.e.*, land expectation value or LEV). The maximisation of the LEV criterion allowed for the identification of the best adaptation strategies in terms of timber revenue. We also analysed the impact of adaptation decisions on carbon sequestration by means of three different carbon-accounting methods (*i.e.,* market value, shadow price, and social cost of carbon). The results show that diversification reduces the loss in timber volume due to drought-induced risk of forest dieback and increases LEV, but also reduces carbon storage. The trade-offs between the financial balance and the carbon balance, and the underlying question of the additivity (or not) of the two adaptation strategies are discussed.

Keywords: Drought; Adaptation; Climate change; Mixed forest; Economics; Carbon.

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1. Introduction

Drought is a natural phenomenon affecting forest productivity and health especially when its intensity is extreme. Abundant evidence has been published regarding the link that exists between drought intensity, crown condition, and mortality, both in Europe (Seidl *et al.*, 2011) and globally (Allen *et al.*, 2010). These impacts result in economic losses for forest owners and amenities losses for the whole society (*e.g.,* reduced carbon sequestration). In France, the extreme drought events of 1976 and 2003 caused great damage (Bréda *et al.*, 2004; Bréda *et al.*, 2006). Severe droughts are thought to be rare phenomena, but their frequency might increase in the future as a consequence of climate change (IPCC, 2013).

While forests are expected to adapt naturally, spontaneous forest adaptation will not be fast enough to keep up with the pace of climate change. Consequently, risk management responses to climate change are required to cope with the increasing risk of drought-induced dieback (Spittlehouse and Stewart, 2003). Water-saving forest management can mitigate the intensity and duration of water shortage periods and their related damage; and therefore increase the trees' adaptive capacity to a changing climate (Bréda and Badeau, 2008).

Adapting forests also means maintaining the services they provide. One such service is carbon sequestration through photosynthesis, which is essential to mitigate climate change ("forests for adaptation", Locatelli *et al.*, 2010). The French government has made several commitments in this field, such as abiding by the terms of the Paris Agreement and achieving carbon neutrality by 2050. The forest sector is an essential lever to achieve these goals (Kolström *et al.*, 2011).

Management strategies can increase the resistance of forest ecosystems. Diversification is a management-based adaptation option. From an economic point of view, investing in a combination of different financial assets might reduce the risk (Markowitz, 1952). Diversifying forest stands can therefore lead to hedging from the climate fluctuations caused by climate change and its related extreme events.

In this paper, two types of diversification strategies are considered: composition diversification and structure diversification. The former means shifting from monocultures to stands composed of two or more species. Mixing species can have positive effects such as favouring tree complementarity and increasing stand productivity (Lebourgeois *et al.*, 2013; Forrester, 2014). However, it can also have adverse effects such as an increase in the competition for water resources (Grossiord *et al.,* 2014; Bonal *et al.*, 2017). These positive or negative effects seem to be dependent on both the context (*e.g.*, soil, climate) and the species mix. The latter consists of shifting from even-aged to uneven-aged silviculture, *i.e.,* having different classes of tree diameter in the same stand. Jacobsen and Helles (2006) stated that the stability of forests granted by the continuous cover can lead to a better resilience to natural hazards.

In this context, a legitimate question is whether forest stand diversification constitutes an economically favourable adaptation option when it comes to reducing drought-induced risk. To answer this question, we analysed the economic costs and benefits of management-based adaptation strategies from a private forest owner's perspective, while considering the impact of these decisions on carbon storage. Few studies have tackled the issue of adaptation to climate change using a forest economics approach. Drought-induced risk of forest dieback is often overlooked in economic analyses even though it is one of the most damageable disturbances for forests. To the best of our knowledge, only Bréda and Brunette (2019) and Brèteau-Amores *et al.*

(2019) have investigated the adaptation to drought-induced risk. Moreover, composition diversification has rarely been analysed as a potential adaptation strategy (Yousefpour and Hanewinkel, 2014; Jönsson *et al.*, 2015) and never for structure diversification.

The objective of this paper was to test and compare different diversification strategies in terms of composition and structure as potential adaptation means for reducing drought-induced risk of forest dieback from an economic perspective. To this end, we focused on beech stands located in the Grand-Est region, France. We used an individual-based model to simulate forest growth under two different scenarios of climate change, namely the representative concentration pathways (RCP) 4.5 and 8.5 (IPCC, 2013). More precisely, we tested two types of diversification that we first analysed separately and then jointly: (i) mixture of beech species with oak species and (ii) mixture of different tree diameter classes (*i.e.,* uneven-aged forest). We also considered the loss associated with drought-induced risk of forest dieback from a financial perspective and in terms of carbon sequestration. The model predictions were used as inputs in the traditional forest economic approach based on land expectation value (LEV). The maximisation of the LEV criterion enabled us to identify the best adaptation strategies, using a strict financial perspective or a more holistic economic approach that also accounted for carbon storage. To account for the economic value of carbon sequestration, we considered three accounting methods, *i.e.,* market value, shadow price, and social cost of carbon. We tested whether (i) diversification is a good adaptation option to reduce drought-induced risk of forest dieback in terms of timber production and carbon storage; (ii) diversification and combining both diversification strategies lead to synergies; (iii) trade-offs between the financial balance and the carbon balance (adaptation *vs.* mitigation) are possible; (iv) carbon price has an impact on (i).

The rest of the paper is structured as follows. The material and methods are presented in Section 2. Section 3 provides the main results. The results are discussed in Section 4, and Section 5 concludes.

2. Material and methods

2.1. Study area: Grand-Est region and species of interest

The Grand-Est region is one of the most afforested region in France with more than a third of its area covered by forests, of which 42% are privately owned[7]. Broadleaved species are the most abundant ones and they provide 64% of the commercial value of timber[1]. Among them, European beech (*Fagus sylvatica* L.), sessile oak (*Quercus petraea* Liebl.) and pedunculate oak (*Quercus robur* L.) are the three main species[3].

Repeated drought events are expected to cause a decline in beech productivity in a near future (Charru *et al.*, 2010). Mixed stands are sometimes proposed as a suitable adaptation option. Beech and oak species are frequently co-occurring species as they share a number of common ecological requirements and characteristics (Rameau *et al.*, 1989). Moreover, oak is a more drought-tolerant species than beech (Scharnweber *et al.*, 2011) and can increase drought resistance and resilience of beech due to inter-specific facilitation (Zapater *et al.*, 2011).

[7] Source: French National Forest Inventory (IGN, 2019).

2.2. Methods

To compare composition and structure diversifications as potential adaptation strategies to reduce drought-induced risk, we defined ten management-based scenarios and simulated their forest growth. Model predictions were used as inputs to compute the land expectation value (LEV) for each scenario. All these elements are represented in Figure II.1 and described in the following sub-sections.

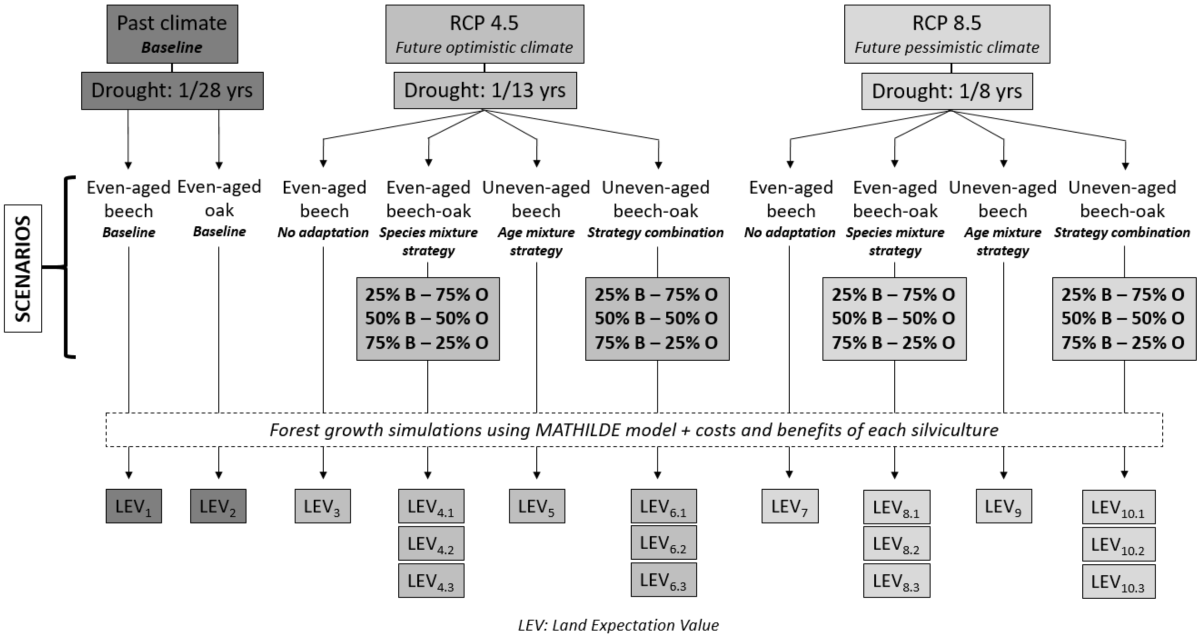

Figure II.1: Schematic representation of the methodology: From scenario definition to economic evaluation.

2.2.1. Scenarios tested

The management scenarios were defined according to tree species and stand structures: pure and even-aged beech/oak stand, pure and uneven-aged beech/oak stand, mixed and even-aged stand (with a respective ratio of beech to oak of 25:75, 50:50, or 75:25), mixed and uneven-aged stand (with the same ratios) (Figure II.1).

These management scenarios were tested in conjunction with three climate scenarios: a reference climate, the RCP 4.5 and the RCP 8.5. All this resulted in a total of 18 scenarios: Two baseline scenarios in a reference climate plus eight scenarios in two different climate projections. The two baselines and the eight scenarios are summarized in Table II.1. Additionally, even-aged and uneven-aged oak stands were simulated in order to test the second hypothesis (synergies of the adaptation strategies).

To project drought occurrence, the growth model required the recurrence of drought events as input. These recurrences were defined from daily soil water deficit computed through a daily forest water balance model BILJOU© (Granier *et al.*, 1999). The computation of the most exceptional drought events (*i.e.,* known in the reference period to induce beech dieback) yielded the respective recurrences of 28, 13, and 8-year intervals. More details on the computation are provided in the Supplementary Material Section (A).

Table II.1: The different scenarios considered and their distinctive code.

Code	**Scenario**
Baseline_B	Benchmark, current even-aged beech stand
Baseline_O	Benchmark, even-aged oak stand in current conditions
B_EA	Even-aged beech stand without adaptation
Mix25_EA	Even-aged mixed stand with a ratio 25:75 of beech and oak proportions
Mix50_EA	Even-aged mixed stand with a ratio 50:50 of beech and oak proportions
Mix75_EA	Even-aged mixed stand with a ratio 75:25 of beech and oak proportions
B_UA	Uneven-aged beech stand
Mix25_UA	Uneven-aged mixed stand with a ratio 25:75 of beech and oak proportions
Mix50_UA	Uneven-aged mixed stand with a ratio 50:50 of beech and oak proportions
Mix75_UA	Uneven-aged mixed stand with a ratio 75:25 of beech and oak proportions

2.2.2. Forest growth simulation

We used MATHILDE, a stochastic individual-based model, to simulate forest dynamics. The model is described in Fortin and Manso (2016) and Fortin *et al.* (2019).

Forest growth was simulated from inventory data. We created a fictive stand as an inventory data for each management scenario listed in Table II.1. These fictive stands represented typical conditions in the Grand-Est region. Since MATHILDE tends to overestimate the mortality of young trees, inconsistent simulations for even-aged stands younger than 30 years of age were generated (Fortin and Manso, 2016). Therefore, the starting point for our simulations were 30-year-old even-aged stands with 2000 stems/ha. For uneven-aged stands, we assumed that they exhibited a balanced diameter distribution with 200 stems/ha. More details on the fictive stands are provided in the Supplementary Material Section (B). The simulation of tree growth for each stand is described below.

First, inventory data are loaded. Each inventory file contained the tree records of 10 plots of 400 m^2 each. Secondly, we used MATHILDE's built-in harvest algorithm to implement the management scenarios. The algorithm requires some bounds in terms of basal area. Whenever the upper bound is crossed, the harvesting is triggered and the trees are harvested until the lower bound is reached. The bounds were assumed to reproduce the management of even-aged and uneven-aged stands (see Table II.C.1 in the Supplementary Material Section). In the case of even-aged stands, the final cut was assumed to be carried out when either the dominant diameter reached 70 cm or the number of stems fell below 100 stems per hectare. The first condition is the one that normally applied without natural disturbances. The second condition is usually met when natural disturbances occur and the stand is deemed to be too depleted to recover. We enabled the recruitment of new trees in uneven-aged stands to keep the forest dynamics going, but not for even-aged stands in order to compute one rotation length at a time. These management scenarios were simulated under reference climate and RCPs 4.5 and 8.5 (Figure II.1). Stochastic simulations in MATHILDE rely on the Monte Carlo technique. In this study, we computed 1000 realizations for each combination of climate and management scenario. The Monte Carlo technique provides a prediction of the stand evolution as well as the uncertainty associated with this prediction. Each realization represents the mean evolution of the 10 plots that compose the fictive stand.

Thirdly, MATHILDE is implemented in the CAPSIS platform (Dufour-Kowalski *et al.,* 2012), which contains a carbon accounting tool (CAT, Pichancourt *et al.*, 2018). Each realization of MATHILDE was processed through CAT in order to simulate the corresponding carbon balance. Basically, CAT turned the different realizations into carbon realizations, which were latter analysed in terms of economic benefits. More technical details on MATHILDE and CAT are provided in the Supplementary Material Section (D).

2.2.3. Economic analysis

2.2.3.1. Double-weighted land expectation value

We used the timber volume and carbon realizations from MATHILDE and CAT to perform an economic comparison of the adaptation strategies based on land expectation value (LEV).

The different scenarios listed in Figure II.1 can be seen as an experimental design to assess the effect of different factors on the LEV. More precisely, it enables the following comparisons:

• LEV 1 *vs*. LEV 3 and LEV 1 *vs*. LEV 7: effect of drought.

• LEV 3 *vs*. LEV 4 and LEV 7 *vs*. LEV 8: effect of composition diversification strategy.

• LEV 3 *vs*. LEV 5 and LEV 7 *vs*. LEV 9: effect of structure diversification strategy.

• LEV 3 *vs*. LEV 6 and LEV 7 *vs*. LEV 10: effect of composition diversification combined with structure one.

In a deterministic setting, the LEV can be obtained from the one-single-rotation net present value (NPV) as follows:

$$LEV(T) = NPV(T)\left[\frac{(1+r)^T}{(1+r)^T - 1}\right] \; with \; NPV(T) = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+r)^t} \qquad (1)$$

Whereas in the context of Monte Carlo-based stochastic simulations (where b is the index of the realizations, so that b = 1, 2,..., B), the expectation of the NPV, as a function of a target rotation length T, can be estimated as follows:

$$\hat{E}[NPV(T)] = \frac{1}{B}\sum_{b=1}^{B} NPV\ (\min(H_b, T)) \qquad (2)$$

where H_b is the date of the final harvest in realization b, which is at best equal to the target T or smaller than T in case of early harvest.

The expectation of LEV can then be approximated by the so-called double-weighted LEV as:

$$\hat{E}[LEV(T)] = \frac{1}{B}\sum_{b=1}^{B}\left[NPV\ (\min(H_b,T)) + \frac{\hat{E}[NPV(T)]}{(1+r)^{\min(H_b,T)}}\frac{(1+r)^{\bar{H}(T)}}{(1+r)^{\bar{H}(T)}-1}\right] \tag{3}$$

where $\bar{H}(T) = \sum_{b=1}^{B}\min(H_b,T)\,/B$. In fact, $\bar{H}(T)$ is the mean harvest age for a target rotation length T. If no early harvest was triggered, then $\bar{H}(T) = T$. Otherwise, $\bar{H}(T) < T$. This double-weighted LEV is an approximation of LEV because (i) the true value of LEV is approximated by pooling all the realizations of a Monte Carlo simulation, and (ii) $\hat{E}[NPV(T)]$ is weighted by using the mean rotation length for all cases from the second rotation onwards, as opposed to the effective rotation length for every single outcome. This approximation simplifies greatly the computation of LEV by allowing a negligible approximation error.

In this setting, the forest owner is solely interested in maximizing the financial net return: The forest owner maximizes LEV with respect to *H(T)*. This setting assumes that the management remains the same over time. In equation (3), this assumption implies that the forest owner gets a certain gain on the first rotation and then from the second one the forest owner gets an expected gain based on an average rotation length $\bar{H}(T)$.

In the context of mitigation of climate change, we also considered carbon sequestration in our economic analysis in order to compare LEV maximization and carbon storage maximization. In this setting, the forest owner is also rewarded for provision of carbon services on a yearly basis. This subsidy depends on changes in carbon stocks. Therefore, the forest owner pays a tax when the forest stand is harvested. To compute the benefits from carbon sequestration, we considered the additional carbon stored in the standing timber, the soil and the wood products, and under three different carbon costs (detailed in Section 2.2.3.2). We assumed also that the carbon sequestered in wood products is never released.

The financial net return provided only by timber production is denoted LEV_T and the one considering timber production and carbon sequestration LEV_{T+C}. LEV_T and LEV_{T+C} were maximized by computing their respective optimal stand age, N_T* and N_{T+C}*, at which the even-aged stand is clear-cut or at which the LEV equilibrium is reached for uneven-aged stand.

2.2.3.2. Carbon price scenarios

We considered three carbon costs, which are related to three different carbon accounting methods.

First, the market value of carbon is the current real carbon price. It results from the purchase of certified credits by a certification entity in order to offset carbon emissions. In our case, this implies a market or a label accounting for the carbon sequestered by forests and funding forest projects by the credits. In France, the low-carbon label[8] was created in 2018. It is based on voluntary participation by project leaders and funders (companies, local authorities). The project (afforestation, reforestation, conversion to enhance carbon sequestration) goes through an official certification process and accounts for the carbon it avoids or sequesters. The carbon price varies according to the different projects depending on funders' participation: After discussion with forestry experts, it appears that carbon prices range from 5 to 50 EUR/tC with a majority of projects using a price of 20 to 30 EUR/tC. We chose to use the average price of 28 EUR/tC.

Second, the shadow price of carbon is an estimate set according to the targeted level of emissions. It results from the optimal distribution of carbon emissions abatements across all economic sectors. It is the minimum cost to be paid by society to achieve the objective set (Quinet, 2019). In 2018, the French shadow price was 54 EUR/tC and this value was used in our analysis. To achieve the goal of carbon neutrality, this shadow price should increase to reach 775 EUR/tC by 2050.

Third, the social cost of carbon is also an estimate resulting from the equality between the marginal cost of CO_2 abatement (*i.e.*, the costs of emissions reduction) and the marginal cost of damage (*i.e.,* the benefit of future avoided damage due to this reduction). The social cost of carbon is "an estimate of the total cost of damages generated by each ton of CO_2 that is spewed into the air" (Howard and Sterner, 2014). In our case study, it gives the total value of avoided damage caused by the flow of carbon to the atmosphere in the case of potential total deforestation. We chose to use the floor value of 125 USD/tC (about 110 EUR/tC) proposed by Van den Bergh and Botzen (2014).

3. Results

3.1. Effect of drought recurrence on optimal rotation length, tree mortality, carbon sequestration, and LEV

Table II.2 shows the results of the optimisation of the rotation length taking into account only timber production (N_T*) and the one taking into account both objectives of timber production and carbon sequestration (N_{T+C}*), as well as results in terms of mortality and carbon sequestration.

First, beech (Baseline_B) has a greater optimal rotation length (N_T* and N_{T+C}*) than oak (Baseline_O) in current conditions. A greater recurrence of drought as induced by the RCP 4.5 and 8.5 causes a decrease of both optimal rotation lengths N_T* and N_{T+C}* in even-aged beech stand (B_EA) and even-aged mixed stand with a ratio beech-oak of 50:50 (Mix50_EA). On the other hand, it increases the optimal rotation length of even-aged mixed stand with a ratio beech-oak of 25:75 (Mix25_EA) and 75:25 (Mix75_EA). All uneven-aged stands (B_UA, Mix25_UA, Mix50_UA, and Mix75_UA) settle down at a common value of 220 years that corresponds to the end of the simulation, *i.e.,* they are not affected by drought recurrence.

[8] "Label Bas Carbone".

Table II.2: Optimal rotation length considering the objective of timber production (N_T) and both economic objectives of timber production and carbon sequestration (N_{T+C}*) with a discount rate of 2% and a carbon price of 54 EUR/tC, average yearly mortality rate of trees in percentage (%) and the total mortality in cubic meters (m^3), and total carbon sequestrated in tons (aboveground, belowground and in wood products) for each scenario.*

		Optimal rotation length		**Mortality**		**Carbon**
Scenario		**N_T***	**N_{T+C}***	**%**	**m^3**	
PAST	Baseline_B	135	135	0.55	27	221
	Baseline_O	115	95	1.03	10	195
RCP 4.5	B_EA	125	125	0.62	26	189
	Mix25_EA	117	117	1.55	14	173
	Mix50_EA	117	117	1.71	14	170
	Mix75_EA	117	117	1.85	16	168
	B_UA	220	36	0.31	51	121
	Mix25_UA	220	220	0.87	25	99
	Mix50_UA	220	220	0.95	28	99
	Mix75_UA	220	220	1.04	31	96
RCP 8.5	B_EA	90	90	0.79	16	157
	Mix25_EA	160	160	1.32	21	121
	Mix50_EA	105	100	1.93	14	143
	Mix75_EA	150	150	1.28	23	123
	B_UA	220	36	0.41	37	109
	Mix25_UA	220	220	1.24	20	89
	Mix50_UA	220	220	1.31	23	88
	Mix75_UA	220	220	1.25	28	89

Second, oak has a greater average mortality rate than beech in current conditions, reversely regarding the total mortality in cubic meters. The more recurrent the drought induced by climate change, the higher the mortality rate and reversely for the total mortality of scenarios.

Third, oak stands sequestrate more than beech stands in current conditions. The greater recurrence of drought decreases carbon sequestration.

Fourth, Table II.3 shows the percentage of gain and loss compared to the baseline (Baseline_B or B_EA). Oak provides a higher economic return than beech in current conditions. A greater recurrence of drought decreases LEV, except for Mix25_EA and B_UA from a carbon price of 54 EUR/tC.

Table II.3: Variation of LEV considering only timber production (T) or with carbon sequestration (C) for a carbon price of 28 EUR/tC, 54 EUR/tC, 110 EUR/tC of each scenario compared to the baseline of beech (Baseline_B or B_EA) in percentage, for RCP 4.5 and RCP 8.5[9].

Scenarios		**LEV_T**	**LEV_{T+C}**		
			28 EUR/tC	**54 EUR/tC**	**110 EUR/tC**
PAST	Baseline_B	-	-	-	-
	Baseline_O	251	244	241	234
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	31	31	30	30
	Mix50_EA	40	39	39	37
	Mix75_EA	38	38	37	36
	B_UA	32	27	42	226
	Mix25_UA	290	274	259	232
	Mix50_UA	210	197	186	164
	Mix75_UA	92	84	77	64
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	177	141	115	75
	Mix50_EA	5	-1	-4	-3
	Mix75_EA	-5	-17	-26	-39
	B_UA	94	69	93	289
	Mix25_UA	480	405	351	266
	Mix50_UA	360	300	257	190
	Mix75_UA	179	143	117	76

3.2. Effect of diversification and combined diversification on optimal rotation length, tree mortality, carbon sequestration and LEV

First, in Table II.2, the scenarios of composition diversification (Mix25/50/75_EA) have a lower optimal rotation length compared with the no-adaptation scenario (B_EA). The scenarios of structure diversification (B_UA) and combined diversification (Mix25/50/75_UA) have a higher optimal rotation length than the baseline in the more optimistic climate scenario (RCP 4.5). In the more pessimistic climate scenario (RCP 8.5), adaptation provides a higher optimal rotation length than the baseline.

Second, the scenario of structure diversification has a lower average mortality rate than the baseline, whereas the scenarios of composition and combined diversification have a higher one. Regarding the total mortality, it is more heterogeneous. Both mortality parameters increase with the proportion of beech mainly in RCP 4.5.

[9] We performed a classical sensitivity analysis to evaluate the impact of changes in the discount rate on each scenario analysed. The results of the analysis are provided in the Supplementary Material Section (E).

Third, no adaptation scenario provides a better carbon sequestration than the baseline and the worst case is the combination of strategies.

Fourth, in Table II.3, the best economic return is provided by uneven-aged mixed stand with a ratio beech-oak of 25:75 (Mix25_UA), except in RCP 8.5 with a carbon price of 110 EUR/tC (B_UA). The scenario of combined diversification still provides the best economic return compared with the scenarios of composition and structure (except for the before-mentioned case) diversifications.

3.3. Effect of carbon price on optimal rotation length and LEV

First, in Table II.2, considering one of the two or both objectives does not affect optimal rotation length of beech. While LEV_{T+C} is higher than LEV_T, N_{T+C}* is less than or equal to N_T*: Considering one of the two or both objectives does not affect optimal rotation length of scenarios, except for B_UA, and Mix50_EA in the more severe climate scenario (RCP 8.5) for which N_{T+C}* is lower than N_T*.

Second, in Table II.3, the higher the carbon price, the higher the LEV but the lower the percentage of gain. The carbon price has more impact on the economic return of structure diversification than the other strategies: Under a price of 110 EUR/tC, B_UA is the best scenario in RCP 8.5 and the second best in the small-temperature increment scenario (RCP 4.5). In RCP 4.5, adaptation is always a good strategy, while it can be the worst option, *i.e.,* maladaptation in RCP 8.5. More precisely, integrating a carbon price increases the number of maladaptation scenario (Mix75_EA only, then with Mix50_EA).

4. Discussion

4.1. Diversification is a good adaptation option to reduce drought-induced risk of forest dieback from an economic perspective

Results vary according to drought recurrence and the related climate scenario, the discount rate, the forest economic objectives, and the carbon price (Tables II.2 and II.3). The heterogeneity of the results can be explained by the fact that mixtures introduce new interactions, but not necessarily additive ones. This illustrates the fact that the difference in productivity between diversified stands and monocultures is unclear (Mina *et al.*, 2018).

However, considering the more optimistic climate scenario (RCP 4.5), diversification increases LEV. Regarding the more pessimistic one (RCP 8.5), there is a risk of maladaptation and thus a decrease of LEV compared to the no-adaptation option. The results corroborate our first hypothesis for structure diversification and combined diversification. This is in line with Müller *et al.* (2019) showing uneven-aged stands as more cost-effective than even-aged ones and papers proposing to combine different strategies, among which species mixture to cope with storm risk (Jönsson *et al.*, 2015). On the other hand, composition diversification is still unclear. Only even-aged mixed stands with a ratio beech-oak of 25:75 (Mix25_EA) seem to be a good adaptation option among the three scenarios of composition diversification tested. Optimising species proportions according to forest management objectives before analysing them and instead of fixing them should improve future studies. Moreover, testing different species in mixtures and optimising also the number of species in the stand could be included as well.

4.2. Diversification and combining both diversification strategies lead to synergies

From an economic perspective, the combination of different strategies can be more beneficial for the forest owner than each strategy separately, *i.e.,* synergies between adaptation strategies can appear. We tested this hypothesis through the Pretzsch and Schütze framework (2009). The framework and the resulted tables are provided in the Supplementary Material Section (F).

Diversifying the stand and combining both diversification strategies can lead to synergies on timber volume, which are emphasized by a greater recurrence of drought: From 28% in RCP 4.5 to 85% of scenarios in RCP 8.5 show synergies. Some synergies appear as well as on LEV depending on the discount rate (from 14% for 1% to 100% for 4%). Indeed, complementarity can occur between beech and oak (Zapater *et al.*, 2011) and in tree structure (Jucker *et al.*, 2015) resulting in a greater water uptake thanks to different vertical rooting pattern among species (Zapater *et al.*, 2011). The results corroborate our second hypothesis.

4.3. Financial balance *vs*. carbon balance

Diversification decreases carbon sequestration (Table II.2), contrary to the results of Kirby and Potvin (2007) and Lange *et al.* (2015). Adaptation to drought-induced risk of forest dieback will be in conflict with mitigation of climate change. Our result does not allow us to determine whether trade-offs between the financial balance and the carbon balance are possible or not: The third hypothesis is rejected. It would be interesting to study further different strategies and their trade-offs between adaptation and mitigation of climate change. For this, we need also to integrate different climate change-related risks in our analysis (*i.e.*, multi-risks analysis).

4.4. Valorising carbon decreases the optimal rotation length and increases LEV

When considering timber production alone (N_T*), the optimal rotation length is either more than or equal to the optimal rotation length observed when considering the objectives of timber production and carbon sequestration jointly (N_{T+C}*). This result is not in line with the common literature (Van Kooten *et al.*, 1995; Pajot, 2011) generally showing an increase of rotation length when carbon services are taken into account in addition to timber production and it does not allow integrating carbon payment as suggested by Brèteau-Amores *et al.* (2019). However, Akao (2011) explains that rotation lengths can become shorter when the forest function of sequestering atmospheric carbon is more important than the one of postponing sequestered carbon release. Moreover, Akao mentioned also that the shorter case is likely to occur when the harvested wood products store the sequestered carbon for many years, which is our case. Therefore, optimising only timber production already integrates optimal carbon services. Additionally, carbon valorisation strategies can decrease the rotation length at the same time, which is in line with adaptation recommendations (Spittlehouse and Stewart, 2003).

Integrating carbon value also increases the value of forest stand (LEV), even more so when adaptation is applied. This shows the importance of considering carbon in our analysis and it corroborates our fourth hypothesis. When we integrated the carbon stored in wood products in addition to the remaining aboveground and belowground carbon in forest stand, we found that the carbon price had little impact on the scenario that resulted in the best economic return. Mixed forests will generate a mixed supply (*e.g.*, in volume, species, quality): Integrating future use of wood products, which may have different lifetimes, may improve our analysis. This would make it possible to consider at the same time the effect of the timber production of forest owners with the economic consequences on the downstream of the wood chain through different wood products. Moreover, timber market currently fluctuates and climate change will enhance this fluctuation (Favero *et al.*, 2018): An extension of our study could be to include different trajectories of timber and carbon prices as well.

4.5. Limits and perspectives of the study

In the model, management decisions are driven by basal area and dominant tree diameter, which are the commonly used criteria in forest management. Nevertheless, there was no possibility to maintain diversity, *i.e.,* the proportions of each species and each tree diameter class. A consequence of the first point was the increasing proportion of beech, as it actually occurs in forest stand (Von Lüpke, 1998). The LEV of the adapted stands can thus be higher than estimated. However, this under-estimation can be counterbalanced by the under-estimation of drought effect.

The drought-induced dieback was modelled as a probability of direct overmortality, which does not include the post-drought effects (Power *et al.*, 1995). Moreover, on the computation of drought recurrences, we assumed that the future climate regardless of the RCP will result in the same water balance whatever the structure and the composition of stands, which is not correct. The different vertical rooting pattern of beech and oak (Zapater *et al.*, 2011) and the different leaf area index (LAI) between mixed and pure stands (Jonard *et al.*, 2011) lead to different water uptake in the soil. All these elements should be included in further studies, which require more investigation on mixed stands' ecology.

While diversification can be a good adaptation strategy, the known-how is also important: The implementation of these silviculture treatments currently lacks management knowledge and skills and requires further investigation. In addition to this, we studied two types of diversification. Another one can be to introduce genetic variability with different provenances of species (Lefèvre *et al.*, 2014).

5. Conclusion

Extreme drought events, increasing the tree mortality, result in losses of timber production and carbon sequestration. When considering timber production alone, our study showed that optimizing rotation lengths increases the value of both timber and carbon services. One of the originalities of this study was to examine two types of diversification: structure diversification and composition diversification. Another originality was the combination of stochastic simulations with a frequently used economic approach. Indeed, our study examined the uncertainty of forest owners' revenues related to forest growth and carbon sequestration under two climate scenarios. Our study showed that diversification (composition and structure) could be a good option to reduce drought-induced risk of forest dieback and leads to some synergies in terms of timber productivity (timber volume) and economic value (timber production with or without carbon valorisation). The heterogeneity of our results showed the importance of considering a variety of criteria, climate scenarios, and ecosystem services. To complement our results, future research could study other species and explore additional types of diversification and ecosystem services, such as partitioning between blue and green water. Further studies should also investigate different strategies and associated trade-offs between adaptation and mitigation of climate change in a multi-risks analysis. Finally, to be effective, adaptation of the forest stand need to be integrated to the entire forest sector. As mixed forests will generate a mixed supply, the impact of adaptation strategies on the entire wood chain should be investigated as well.

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Supplementary material

A. Drought recurrences definition

The recurrences of drought events were defined from daily soil water content computed through BILJOU©.

Water balance calculations have been performed for a representative beech stand of Grand-Est region with a medium site fertility (*i.e.,* available soil water content of 100 mm and leaf area index of 5.5) and for the reference climate, RCP 4.5 and RCP 8.5 (data from ARPEGE model).

We assumed that the same water balance results from future climate regardless the RCP and regardless to stand composition and structure.

B. Creation of fictive stands

We created a fictive stand for each management scenario. More precisely, mixed stand of beech and oak has the same density as in monoculture: The introduced species substitutes a part of the current species in the stand (25, 50 or 75%).

Concerning diversification by structure, the stand is defined as a homogeneous uneven-aged one according to the structure triangle in the French forest management. It corresponds to a share of stand basal area by three different diameter classes. In our study, stands are composed of roughly 30% of trees with a DBH of 17.5 – 27.5 cm, 45% of trees with a DBH of 27.5 – 47.5 cm, and 25% of trees with a DBH of more than 47.5 cm.

C. Simulation of forest management

MATHILDE's built-in harvest algorithm requires some bounds in terms of basal area to implement the management scenarios. The bounds are shown in the following table:

Table II.C.1: Basal area bounds (m^2/ha) that were used in the different management scenarios (source: CRPF[10]). The bounds are age dependent for even-aged management scenarios. n/a: not applicable.

Management scenario	Stand age (yrs)	Bounds (m^2/ha)
Even-aged beech	0-50	[14, 18]
	50-70	[18, 22]
	70 until final cut	[22, 26]
Even-aged oak	0-50	[14, 18]
	50 until final cut	[18, 22]
Even-aged mixed stand	0-50	[14, 18]
	50 until final cut	[18, 22]
Uneven-aged beech	n/a	[14, 18]
Uneven-aged oak	n/a	[12, 16]
Uneven-aged mixed stand	n/a	[12, 16]

D. MATHILDE and CAT

MATHILDE is a distance-independent individual-based model that simulates forest dynamics (Fortin and Manso, 2016). MATHILDE is fitted to data from a large network of permanent plots measured over the 1958-2007 period. It is designed to simulate even-aged and uneven-aged stands as well as pure and mixed stands of beech and sessile oak in Northern France. More precisely, it predicts tree mortality, the diameter increment of survivors and the recruitment of new trees over five-year growth periods. The model is composed of different sub-models, which are illustrated on Figure II.D.1.

The climate sub-model is fitted to data from SAFRAN model over the 1959-2012 period. It predicts the mean seasonal temperature over a period, depending on the initial year of the period and the occurrence of drought during the period. The growing season temperature is controlled by a parameter driving its increase. This parameter depends on the given climate scenario and changes when a drought occurs during the period.

The mortality sub-model encompasses many explanatory variables such as tree species, diameter at breast height (DBH, 1.3 m in height), basal area of trees with DBH larger than the subject tree as well as the occurrence of drought, windstorm and harvesting (Manso *et al.*, 2015a). The effects of drought and windstorm are the average of those observed over the last 60 years.

The diameter-increment sub-model predicts the increment of a given tree over a period (Manso *et al.*, 2015b). The explanatory variables are tree species, DBH, basal area of trees with DBH larger than the subject tree, plot basal area, harvest occurrence, and mean seasonal temperature during the time interval.

The sub-model of tree recruitment predicts the number of trees that cross the threshold of 7.5 cm for each species. The explanatory variables are the all-species basal area as well as the basal

[10] Regional Center for Privately-Owned Forests.

area of the species. In addition to the aforementioned sub-models, MATHILDE also includes a model of height-diameter relationships (Fortin *et al.,* 2019).

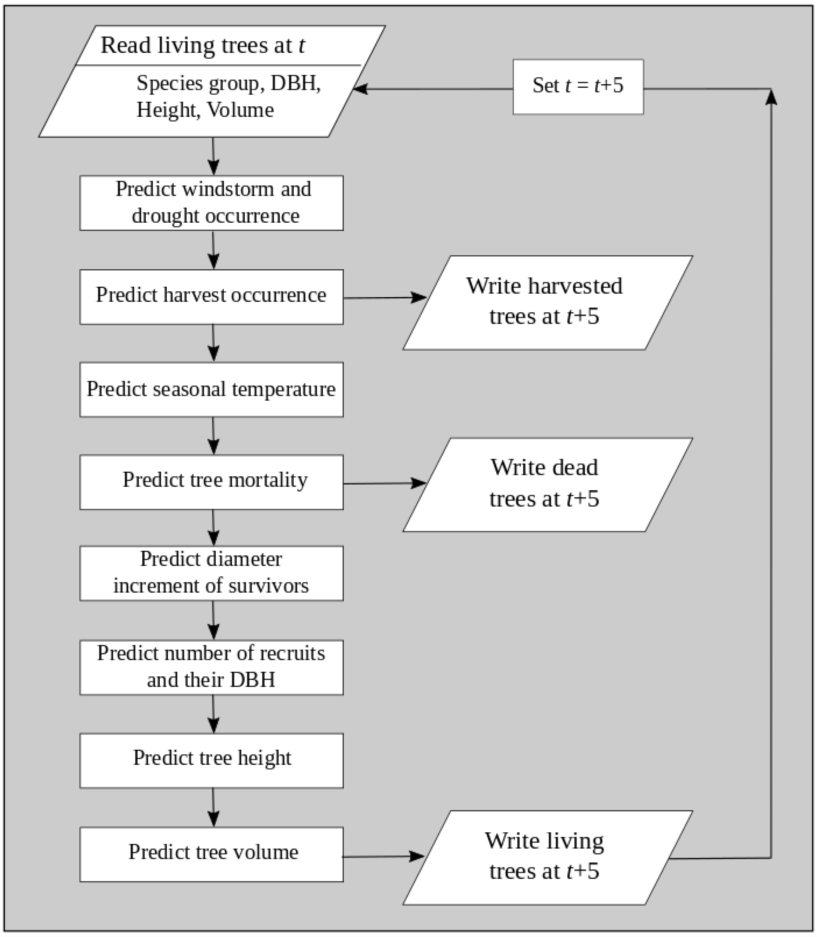

Figure II.D.1: Flowchart of the sub-models composing MATHILDE.

MATHILDE is designed to simulated forest growth from inventory data in a stochastic manner using the Monte Carlo technique. This method provides a prediction of the stand evolution as well as the uncertainty associated with this prediction. Confidence interval bounds are derived using the percentile rank method (Efron and Tibshirani, 1993). The model implements an algorithm that triggers the harvesting based on plot basal area and a target dominant diameter, *i.e.,* the mean diameter of the 100 thickest trees per hectare. Once the harvesting is triggered, a sub-model of tree harvest predicts the probability that an individual tree is harvested (see Manso *et al.*, 2018).

MATHILDE is implemented in the CAPSIS platform (Dufour-Kowalski *et al.,* 2012), which contains a carbon accounting tool (CAT, Pichancourt *et al.*, 2018). CAT allows for the representation of complex emission life cycles inherent to managed forests. It takes into account the main issues related to carbon accounting tools, such as the numerous uncertainties, risk of carbon leakage and double counting. The assessment of the carbon balance is also supported by built-in Monte Carlo error propagation methods. In addition to the IPCC standards, CAT also provides estimates of

(i) cumulative material and energy substitution, that is the greenhouse gas emissions avoided when a harvested wood product (HWP) replaces an alternative product;
(ii) cumulative fossil fuel carbon emissions during the life cycle of the different HWP;
(iii) the accumulation of non-degradable HWP at solid waste disposal site (SWDS), and
(iv) cumulative methane (CH_4) emissions caused by the degradation of HWP at SWDS. By default (semi-aerobic conditions), CAT assumes that 25% of the carbon emitted from the SWDS is methane. The non-degradable part of carbon that accumulates at a SWDS is assumed to be permanently sequestered.

Simulations are run by default under global warming potential factors of the fifth assessment report on climate change (IPCC, 2013). Results are exported in carbon units with the probability level of the confidence intervals equal to 0.95 by default.

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E. Land expectation value and sensitivity analysis of discount rate

We performed a sensitivity analysis of discount rate. The results are presented in Table II.E.1 and are ranked by their economic return (LEV) for each climate scenario. The detailed gain and loss compared to the baseline (Baseline_B and B_EA) are provided in Table II.E.2.

Table II.E.1: Scenarios code ranked by their economic return for each climate scenario (past, RCP 4.5 and RCP 8.5) and for four discount rates (1%, 2%, 3%, and 4%). The four tables correspond to LEV considering only timber production (T) (top left) or with carbon sequestration (T+C) for a carbon price of 28 EUR/tC (top right), 54 EUR/tC (bottom left), and 110 EUR/tC (bottom right). Each management scenario is related to a colour.

T	**0.01**	**0.02**	**0.03**	**0.04**
PAST	Baseline_O	Baseline_O	Baseline_O	Baseline_O
	Baseline_B	Baseline_B	Baseline_B	Baseline_B
RCP 4.5	Mix25_UA	Mix25_UA	Mix25_UA	Mix75_EA
	Mix50_UA	Mix50_UA	Mix50_UA	Mix50_EA
	B_EA	Mix75_UA	Mix50_EA	Mix25_EA
	Mix75_UA	Mix50_EA	Mix75_EA	Mix25_UA
	B_UA	Mix75_EA	Mix25_EA	Mix50_UA
	Mix50_EA	B_UA	Mix75_UA	Mix75_UA
	Mix75_EA	Mix25_EA	B_UA	B_UA
	Mix25_EA	B_EA	B_EA	B_EA
RCP 8.5	Mix25_UA	Mix25_UA	Mix25_UA	Mix25_EA
	Mix50_UA	Mix50_UA	Mix50_UA	Mix25_UA
	Mix75_EA	Mix75_UA	Mix25_EA	Mix50_UA
	Mix50_EA	Mix25_EA	Mix75_UA	Mix75_UA
	B_EA	B_UA	B_UA	B_UA
	Mix75_UA	Mix50_EA	Mix50_EA	Mix50_EA
	B_UA	B_EA	B_EA	B_EA
	Mix25_EA	Mix75_EA	Mix75_EA	Mix75_EA

T+C_28	**0.01**	**0.02**	**0.03**	**0.04**
PAST	Baseline_O	Baseline_O	Baseline_O	Baseline_O
	Baseline_B	Baseline_B	Baseline_B	Baseline_B
RCP 4.5	Mix25_UA	Mix25_UA	Mix25_UA	Mix50_EA
	Mix50_UA	Mix50_UA	Mix50_UA	Mix75_EA
	B_EA	Mix75_UA	Mix50_EA	Mix25_EA
	Mix75_UA	Mix50_EA	Mix75_EA	Mix25_UA
	B_UA	Mix75_EA	Mix25_EA	Mix50_UA
	Mix50_EA	Mix25_EA	Mix75_UA	Mix75_UA
	Mix75_EA	B_UA	B_UA	B_UA
	Mix25_EA	B_EA	B_EA	B_EA
RCP 8.5	Mix25_UA	Mix25_UA	Mix25_UA	Mix25_EA
	Mix50_UA	Mix50_UA	Mix50_UA	Mix25_UA
	Mix50_EA	Mix75_UA	Mix25_EA	Mix50_UA
	B_EA	Mix25_EA	Mix75_UA	Mix75_UA
	Mix75_EA	B_UA	B_UA	B_UA
	Mix75_UA	B_EA	B_EA	B_EA
	B_UA	Mix50_EA	Mix50_EA	Mix50_EA
	Mix25_EA	Mix75_EA	Mix75_EA	Mix75_EA

T+C_54	**0.01**	**0.02**	**0.03**	**0.04**
PAST	Baseline_O	Baseline_O	Baseline_O	Baseline_O
	Baseline_B	Baseline_B	Baseline_B	Baseline_B
RCP 4.5	Mix25_UA	Mix25_UA	Mix25_UA	Mix50_EA
	Mix50_UA	Mix50_UA	Mix50_UA	Mix75_EA
	B_EA	Mix75_UA	Mix50_EA	Mix25_EA
	B_UA	B_UA	Mix75_EA	Mix25_UA
	Mix75_UA	Mix50_EA	Mix25_EA	Mix50_UA
	Mix50_EA	Mix75_EA	Mix75_UA	Mix75_UA
	Mix75_EA	Mix25_EA	B_UA	B_UA
	Mix25_EA	B_EA	B_EA	B_EA
RCP 8.5	Mix25_UA	Mix25_UA	Mix25_UA	Mix25_EA
	Mix50_UA	Mix50_UA	Mix50_UA	Mix25_UA
	B_UA	Mix75_UA	Mix25_EA	Mix50_UA
	B_EA	Mix25_EA	Mix75_UA	Mix75_UA
	Mix50_EA	B_UA	B_UA	B_UA
	Mix75_EA	B_EA	B_EA	B_EA
	Mix75_UA	Mix50_EA	Mix50_EA	Mix50_EA
	Mix25_EA	Mix75_EA	Mix75_EA	Mix75_EA

T+C_110	**0.01**	**0.02**	**0.03**	**0.04**
PAST	Baseline_O	Baseline_O	Baseline_O	Baseline_O
	Baseline_B	Baseline_B	Baseline_B	Baseline_B
RCP 4.5	B_UA	Mix25_UA	Mix25_UA	Mix50_EA
	Mix25_UA	B_UA	B_UA	Mix75_EA
	Mix50_UA	Mix50_UA	Mix50_UA	Mix25_EA
	B_EA	Mix75_UA	Mix50_EA	Mix25_UA
	Mix75_UA	Mix50_EA	Mix75_EA	B_UA
	Mix50_EA	Mix75_EA	Mix25_EA	Mix50_UA
	Mix75_EA	Mix25_EA	Mix75_UA	Mix75_UA
	Mix25_EA	B_EA	B_EA	B_EA
RCP 8.5	B_UA	B_UA	Mix25_UA	Mix25_EA
	Mix25_UA	Mix25_UA	B_UA	Mix25_UA
	Mix50_UA	Mix50_UA	Mix50_UA	B_UA
	B_EA	Mix75_UA	Mix25_EA	Mix50_UA
	Mix50_EA	Mix25_EA	Mix75_UA	Mix75_UA
	Mix75_EA	B_EA	Mix50_EA	B_EA
	Mix75_UA	Mix50_EA	B_EA	Mix50_EA
	Mix25_EA	Mix75_EA	Mix75_EA	Mix75_EA

Table II.E.2: Variation of LEV (in percentage terms) of each scenario compared to the baseline of beech (Baseline_B or B_EA), for RCP 4.5 and RCP 8.5 and for four discount rates (1%, 2%, 3%, and 4%). The four tables correspond to LEV considering only timber production (T) (top left) or with carbon sequestration (T+C) for a carbon price of 28 EUR/tC (top right), 54 EUR/tC (bottom left), and 110 EUR/tC (bottom right).

T	Scenarios	0.01	0.02	0.03	0.04
PAST	Baseline_B	-	-	-	-
	Baseline_O	211	251	317	376
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	-83	31	349	1202
	Mix50_EA	-79	40	374	1285
	Mix75_EA	-81	38	372	1287
	B_UA	-54	32	154	349
	Mix25_UA	73	290	622	1157
	Mix50_UA	20	210	483	920
	Mix75_UA	-40	92	271	552
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	-33	177	643	1691
	Mix50_EA	7	5	3	2
	Mix75_EA	12	-5	-17	-24
	B_UA	-22	94	222	391
	Mix25_UA	230	480	823	1283
	Mix50_UA	110	360	646	1026
	Mix75_UA	-7	179	369	612

T+C_28	Scenarios	0.01	0.02	0.03	0.04
PAST	Baseline_B	-	-	-	-
	Baseline_O	205	244	313	362
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	-78	31	337	1075
	Mix50_EA	-76	39	365	1150
	Mix75_EA	-76	38	359	1133
	B_UA	-54	27	144	304
	Mix25_UA	77	274	595	1030
	Mix50_UA	21	197	461	818
	Mix75_UA	-40	84	257	486
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	-41	141	549	1468
	Mix50_EA	1	-1	-2	-3
	Mix75_EA	-2	-17	-27	-33
	B_UA	-32	69	181	330
	Mix25_UA	195	405	706	1111
	Mix50_UA	82	300	552	886
	Mix75_UA	-19	143	309	523

T+C_54	Scenarios	0.01	0.02	0.03	0.04
PAST	Baseline_B	-	-	-	-
	Baseline_O	199	241	308	350
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	-74	30	326	953
	Mix50_EA	-72	39	353	1020
	Mix75_EA	-72	37	347	1004
	B_UA	-16	42	146	271
	Mix25_UA	79	259	571	910
	Mix50_UA	20	186	442	720
	Mix75_UA	-40	77	245	424
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	-48	115	481	1312
	Mix50_EA	-3	-4	-4	-1
	Mix75_EA	-13	-26	-35	-40
	B_UA	39	93	178	313
	Mix25_UA	170	351	622	991
	Mix50_UA	63	257	483	788
	Mix75_UA	-28	117	266	461

T+C_110	Scenarios	0.01	0.02	0.03	0.04
PAST	Baseline_B	-	-	-	-
	Baseline_O	186	234	284	322
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	-65	30	259	767
	Mix50_EA	-64	37	281	820
	Mix75_EA	-64	36	276	808
	B_UA	96	226	403	647
	Mix25_UA	79	232	453	725
	Mix50_UA	15	164	346	569
	Mix75_UA	-43	64	184	328
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	-57	75	374	1009
	Mix50_EA	-5	-3	0	0
	Mix75_EA	-29	-39	-38	-39
	B_UA	180	289	461	700
	Mix25_UA	138	266	488	757
	Mix50_UA	40	190	375	598
	Mix75_UA	-41	76	199	341

F. Synergy analysis of adaptation strategies

First, the overyielding is defined as a higher observed parameter P_{mix} in the mixed stand than the expected parameter $\widehat{P_{mix}}$ (Pretzsch and Schütze, 2009), *i.e.*,

$$P_{mix} > \widehat{P_{mix}} \leftrightarrow P_{mix} > q_1.P_1 + q_2.P_2$$

where q_1 and q_2 are the respective mixing proportions of species 1 and species 2, and P_1 and P_2 the respective parameter of species 1 and species 2 in monoculture.

Then, a transgressive overyielding of the mixed stand can be observed, when the observed parameter P_{mix} is higher than the parameter of both species in monoculture (P_1 and P_2) (Pretzsch and Schütze, 2009), *i.e.*,

$$P_{mix} > P_1 \text{ and } P_{mix} > P_2$$

The tested parameters were the total volume harvested and the land expectation value. The results are presented in Tables II.F.1 and II.F.2. An overyielding is represented by a coefficient of 1 and a transgressive overyielding by a coefficient of 1+. An absence of overyielding is represented by a coefficient of 0.

Table II.F.1: Results of the tested synergy of mixed stands in total volume harvested characterised by overyielding (coefficient 1) or transgressive overyielding (coefficient 1+) or absence (coefficient 0) for each scenario and considering four discount rates (1%, 2%, 3%, and 4%).

Scenario		**0.01**	**0.02**	**0.03**	**0.04**
RCP 4.5	B_EA	-	-	-	-
	Mix25_EA	0	0	0	1
	Mix50_EA	0	0	1+	1+
	Mix75_EA	0	0	1+	1+
	B_UA	0	0	1+	1+
	Mix25_UA	0	1	0	0
	Mix50_UA	0	1	0	0
	Mix75_UA	0	0	0	0
RCP 8.5	B_EA	-	-	-	-
	Mix25_EA	1+	1+	1+	1+
	Mix50_EA	1+	1+	1+	0
	Mix75_EA	1+	1+	1+	1+
	B_UA	0	0	0	0
	Mix25_UA	0	1	1	1
	Mix50_UA	0	1	1	1
	Mix75_UA	0	1	1	1

Table II.F.2: Results of the tested synergy of mixed stand on LEV considering only timber production (T) or with carbon sequestration for a carbon price of 28 EUR/tC, 54 EUR/tC, and 110 EUR/tC, characterised by overyielding (coefficient 1) or transgressive overyielding (coefficient 1+) or absence (coefficient 0) for each scenario and considering four discount rates (1%, 2%, 3%, and 4%).

		0.01				**0.02**				**0.03**				**0.04**			
	Scenario	**T**	**28**	**54**	**110**	**T**	**28**	**54**	**110**	**T**	**28**	**54**	**110**	**T**	**28**	**54**	**110**
RCP 4.5	B_EA	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mix25_EA	0	0	0	0	0	0	0	0	1	1	1	0	1+	1+	1+	1+
	Mix50_EA	0	0	0	0	0	0	0	0	1	1	1	1	1+	1+	1+	1+
	Mix75_EA	0	0	0	0	0	0	0	0	1	1	1	1	1+	1+	1+	1+
	B_UA	0	0	0	0	0	0	0	1	1	1	1	1+	1	1	1	1+
	Mix25_UA	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
	Mix50_UA	0	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1
	Mix75_UA	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	0
RCP 8.5	B_EA	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Mix25_EA	0	0	0	0	0	0	0	0	1+	1+	1+	1+	1+	1+	1+	1+
	Mix50_EA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mix75_EA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	B_UA	0	0	0	1	0	0	0	1	1	1	1	1+	1	1	1	1+
	Mix25_UA	0	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1
	Mix50_UA	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Mix75_UA	0	0	0	0	0	0	0	0	1	1	1	0	1	1	1	0

Chapter III

Composition diversification *vs*. structure diversification: How to conciliate timber production and carbon sequestration objectives under drought and windstorm risks in forest ecosystems

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Abstract

Forests provide ecosystem services such as timber production and carbon sequestration. However, forests are sensitive to climate change. As the pace of climate change continues to accelerate, climate-induced damages are expected to cause substantial amenity losses for the society, in addition to financial losses for forest owners. Forests in the Grand-Est region, France, are dominated by European beech, for which a decline in productivity is anticipated due to repeated drought events induced by climate change. These forest ecosystems are also threatened by windstorm events. Tree species diversification is one of the many forest management strategies that can help beech forests to adapt to increased risks of severe drought and windstorm events. This article presents the results of a study that compared different forest adaptation strategies from an economic perspective with the objective to reduce drought- and windstorm-induced risks of dieback. In this study, two types of diversification strategies were analysed, first separately then jointly. These are: mixing beech with oak (composition diversification) and shifting from an even-aged to an uneven-aged forest (structure diversification). We also considered two types of loss associated with different recurrences of drought and windstorm risks, namely financial loss and reduction of carbon sequestration capacity. We combined a forest growth simulator with a forest economic approach through the computation of land expectation value (LEV). The maximisation of the LEV criterion made it possible to identify the most economically effective adaptation strategies. Results show that diversification increases timber production and LEV, but reduces carbon storage. The two risks as well as the adaptation strategies show some synergies. Finally, trade-offs between the financial balance and the carbon balance (*i.e.,* adaptation *vs*. mitigation) are achievable.

Keywords: Forest; Drought; Windstorm; Adaptation; Climate change; Mixture; Economics; Multi-risks; Carbon.

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1. Introduction

Drought is a major disturbance affecting forest health worldwide (Zierl, 2004; Allen *et al.*, 2010). In Europe, trees are suffering from severe droughts occurring especially in early summer (Bréda and Badeau, 2008), which result in a decrease of biomass production and in an increase of tree mortality (Seidl *et al.*, 2011). Drought-induced damage implies economic losses for forest owners and a loss of amenities (*e.g.*, carbon sequestration) for the society. These impacts could become even more important in a near future as the frequency, duration, and intensity of extreme natural events is likely to increase with climate change (Dale *et al.*, 2001).

During any given rotation, forest stands can be affected by several hazards. In France, droughts and windstorms are the two main damaging abiotic risks (Rouault *et al.*, 2006; Bonnesoeur *et al.*, 2013) affecting the overall carbon sequestration capacity of forests (Thurig *et al.*, 2013). Like droughts, severe windstorms negatively affect forest health, damaging forest stands especially in winter and late autumn (Valinger and Fridman, 2011). Given that forest ecosystems play a major role in mitigating the effects of climate change through carbon sequestration, there is growing concern about how this mitigation capacity can be maintained as risks increase (Locatelli *et al.*, 2010; Kolström *et al.*, 2011). In this context, investigating the cumulative impact of several extreme events on forest stands can provide further insight into potential adaptation strategies.

As the natural and spontaneous forest adaptation process is unable to keep up with the pace of climate change, well-suited forest management strategies need to be implemented (Spittlehouse and Stewart, 2003). Several strategies can maintain forest ecosystems' resilience through silvicultural management (Spittlehouse and Stewart, 2003) such as reducing rotation length or decreasing stand density. Adaptation strategies generate new management costs and benefits for forest owners (Kolström *et al.*, 2011) and, therefore, must be suitable for all major climatic disturbances. Diversification can be used to hedge trees from climate fluctuations and disturbances associated with climate change. This adaptation strategy can contribute to develop more stable forest stands. In this paper, two types of diversification strategies are compared. The first one, composition diversification, relates to stand composition and entails shifting from monocultures to mixed stands with two or more species. This strategy can lead to complementarity in tree structure or "canopy packing" (Jucker *et al.*, 2015), which in turn, can increase tree resistance to damage (Lebourgeois *et al.*, 2013; Jactel *et al.*, 2017). Indeed, different vertical rooting patterns among species can result in a higher water uptake (Zapater *et al.*, 2011) and a greater wind resistance of the stand (Mason and Valinger, 2013). Mixing species can also increase forest productivity (Forrester, 2014) and other ecosystem services (Duncker *et al.*, 2012) such as carbon sequestration (Kirby and Potvin, 2007; Lange *et al.*, 2015). However, it can increase tree competition for water resources (Bonal *et al.*, 2017) leading to lower soil moisture availability (Grossiord *et al.*, 2014). The second type of diversification strategy, structure diversification, leads to a modification of the stand structure by introducing different diameter classes within the same stand. Moving from even-aged to uneven-aged silviculture increases the stability of the entire stand structure (Hanewinkel *et al.*, 2014). This strategy also enhances stand resilience to natural hazards (Jacobsen and Helles, 2006) as the understorey trees allow for faster recovery after disturbance (Stanturf *et al.*, 2007). However, uneven-aged silviculture can increase the vulnerability of the stand as a result of the successive thinnings that reduce the stabilizing effect of crown contact that normally takes place in even-aged stands (Mason and Valinger, 2013).

In this context, the main research question addressed in this paper is whether diversification of forest stands can be used as an economically effective adaptation strategy in response to future drought- and windstorm-induced risks of forest dieback. We propose an analysis of the economic costs and benefits of diversification from a private forest owners' perspective, *i.e.*, based on timber production and carbon storage. In the literature, few studies have dealt with forest adaptation to climate change using an economic approach. To the best of our knowledge, only Bréda and Brunette (2019) and Brèteau-Amores *et al.* (2019; 2020) have studied the economic impact of forest adaptation to drought-induced risk. Additonally, while some studies have investigated the impacts of windstorm damage on forests (Brunette *et al.*, 2015; Rakotoarison and Loisel, 2017), only a few papers deal with forest adaptation against windstorm risk (Jönsson *et al.,* 2015; Müller *et al.*, 2019). Moreover, limited attention has been paid to carbon loss in addition to economic loss (Yousefpour and Hanewinkel, 2014; Brèteau-Amores *et al.*, 2019; Müller *et al.*, 2019; Brèteau-Amores *et al.*, 2020). According to Montagné-Huck and Brunette (2018), most multi-hazard approaches used in other disciplines typically do not include any economic analysis: Only Petucco and Andrés-Domenech (2018) combined windstorm with another natural risk (pests). However, as pointed out by Montagné-Huck and Brunette (2018), Petucco and Andrés-Domenech (2018) examined these two risk factors independently, *i.e.,* without considering possible interactions. To the best of our knowledge, there is no previous study examining the combined effects of drought- and windstorm-induced risks of forest dieback from an economic perspective.

The objective of this paper was to test and then to compare two types of diversification (*i.e.*, composition diversification and structure diversification) as potential adaptation strategies aiming at reducing drought- and windstorm-induced risks of forest dieback from an economic perspective. For this purpose, we focused on beech stands in the Grand-Est region, France. We used an individual-based model to simulate forest growth under two different scenarios of climate change, namely the representative concentration pathways (RCP) 4.5 and 8.5 (IPCC, 2013). More precisely, we tested two types of diversification that we analysed separately and then jointly: (i) mixture of beech species with oak species and (ii) mixture of different tree diameter classes (*i.e.,* uneven-aged forest). We also considered the impact of drought- and windstorm-induced risks from a strict economic standpoint (*i.e.*, financial loss) and in terms of carbon sequestration (*i.e.*, reduction in carbon sequestration capacity). The model predictions were used as inputs in the computation of land expectation value (LEV). The maximisation of the LEV criterion allowed us to identify the best adaptation strategy. To account for the economic value of carbon sequestration, we considered three accounting methods, *i.e.,* market value, shadow price, and social cost of carbon. We investigated whether (i) diversification is a good adaptation strategy to reduce drought- and windstorm-induced risks; (ii) considering both risks simultaneously impacts the results and recommendations compared to investigating each risk separately; (iii) diversifying the stand and implementing both diversification strategies lead to synergies; (iv) carbon price has an impact on (i).

2. Material and methods

2.1. Study area: Drought and windstorm in the Grand-Est region and species of interest

With about one third of its area covered with forests - of which 42% are privately owned - the Grand-Est region is one of French regions with the largest amount of forested land[12]. In this region, forests are dominated by broad-leaved species, such as European beech (*Fagus sylvatica* L.), sessile oak (*Quercus petraea* Liebl.) and pedunculate oak (*Quercus robur* L.). These three species are economically important since they represent 40% of the total timber produced in this region[6].

In the Grand-Est region, drought and windstorm occurrences constitute two major causes of tree mortality (Rouault *et al.*, 2006; Bonnesoeur *et al.*, 2013). The extreme drought episodes of 1976 and 2003 caused a wide range of both short-term and long-term damages (Bréda *et al.*, 2004). In fact, the 2003 drought had more severe consequences than that of 1976 as the heat wave impacts were compounded by a water shortage responsible for stomatal control and loss of canopy refreshment (Bréda *et al.*, 2006). Given the fact that the radial growth of beech is sensitive to edaphic drought, beech productivity is projected to decline (or its range to be restricted) due to repeated drought episodes as intense as in 2003 (Lebourgeois *et al.*, 2005; Charru *et al.*, 2010). In addition to this, severe windstorms have negatively impacted the forest sector of Grand Est region. Before the violent windstorms Lothar and Martin that swept across western and central Europe in 1999 (Bonnesoeur *et al.*, 2013), the Grand-Est region ranked first in France for the production of high-quality beech timber. The 1999 windstorms devastated 176 Mm^3 of roundwood; a volume equivalent to three times the French annual timber harvest (MAP and IFN, 2006).

As recommended in the French windstorm crisis management plan created for the forest sector 2018, stand diversification can be an option to help beech adapt to drought and windstorm episodes. However, the success of this strategy depends on whether the additional species have an impact on the severity of water shortage constraints (Metz *et al.*, 2016). For instance, the admixture of beech with deep-rooting species (*i.e.*, species that take up water in deep soil layers) such as oak (Zapater *et al.*, 2013) or silver fir (Magh *et al.*, 2018) was found to reduce drought stress due to the asynchronous stress reaction pattern of beech and oak (Zapater *et al.*, 2011; Pretzsch *et al.*, 2013). Being more resistant than beech, oak can reduce windstorm damage at the stand level (Mason and Valinger, 2013). Moreover, mixed forests of beech and oak are common in Europe (Pretzsch *et al.*, 2013) and represent more than 10% of the French mixed forests (Morneau *et al.*, 2008).

In France, the two main oak species are sessile oak and pedunculate oak. The former is more resistant to soil water shortage and competition than the latter (Rameau *et al.*, 1989; Sevrin, 1997). However, sessile oaks can be more vulnerable to herbivorous game species, which may result in higher management costs: Fencing might be needed to ensure the successful regeneration of sessile oak forest stands (Sevrin, 1997).

[12] Source: French National Forest Inventory (IGN, 2019).

2.2. Methods

We defined six management-based scenarios and simulated their forest growth. The model predictions were used as inputs to compute land expectation value (LEV) for each scenario. Figure III.1 maps all these elements, which are also described in the following sub-sections.

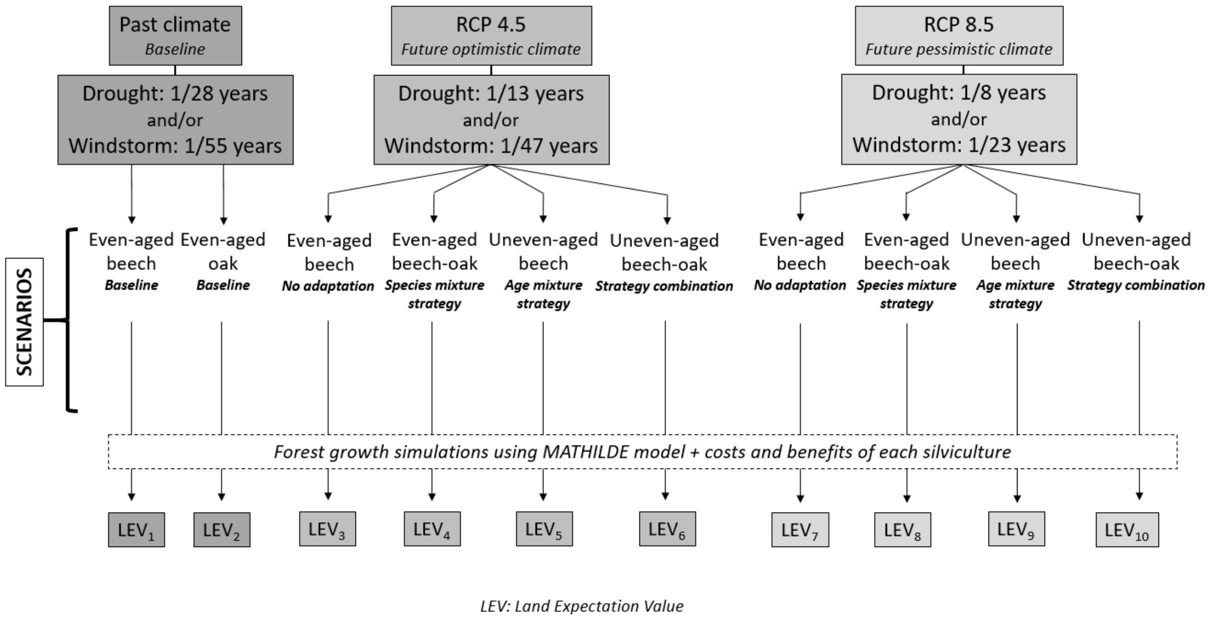

Figure III.1: Schematic representation of the methodology: From scenario definition to economic evaluation.

2.2.1. Scenarios tested

The six scenarios represent different combinations of tree species and stand structures. These are: pure and even-aged beech/oak stand, pure and uneven-aged beech stand, mixed and uneven-/even-aged stand with a 50:50 ratio of beech to oak (Figure III.1). As summarized in Table III.1, two baselines were simulated under past climate conditions and four scenarios were simulated and tested under future climate conditions as determined by the RCP 4.5 and the RCP 8.5 (IPCC, 2013). In addition to these scenarios, both even-aged oak stands and uneven-aged oak stands were simulated in order to test our third hypothesis, *i.e.*, the existence of synergistic effects between the two adaptation strategies under study.

In our simulations, the recurrence of drought and windstorm events were considered as exogenous variables. Regarding the drought recurrence, we followed the methodology used by Brèteau-Amores *et al.* (2020) where the most exceptional drought events (*i.e.,* events known to induce beech dieback during the reference period) were computed using a daily forest water balance model BILJOU© (Granier *et al.*, 1999) under the reference period and two RCP references (*i.e.*, RCP 4.5 and RCP 8.5). The drought recurrences of these three climate scenarios were estimated at 28, 13, and 8-year intervals, respectively. As far as the windstorm occurrence, we computed the most exceptional events (*i.e.,* events inducing damages similar to those caused by the Lothar 1999 windstorm) using Météo France data for the three above-mentioned climate scenarios. The respective recurrences were estimated at 55, 47, and 23-year intervals. More details on the computation of windstorm recurrences are provided in the Supplementary Material Section (A).

Table III.1: The six different scenarios and their respective code.

Code	Scenario
Baseline_B	Benchmark, current even-aged beech stand
Baseline_O	Benchmark, even-aged oak stand in current conditions
B_EA	Even-aged beech stand without adaptation
Mix50_EA	Even-aged mixed stand with a ratio 50:50 of beech to oak
B_UA	Uneven-aged beech stand
Mix50_UA	Uneven-aged mixed stand with a ratio 50:50 of beech to oak

Rouault *et al.* (2006) showed that windstorms could increase tree vulnerability to drought damage. On the other hand, one of the consequences of drought, *i.e.,* the development of root systems capable of taking up water stored in deep soil layers, can provide a better root anchorage and limit the amount of windthrow in the event of windstorms (Stocker, 1976). While these two studies showed some degree of correlation between the effects of windstorms and the effects of droughts, they did not prove the existence of an ecological link between drought risks and windstorm risks. Consequently, we considered and tested drought and windstorm occurrences independently. In other words, we assumed that the occurrence of a windstorm does not increase the likelihood of a drought and *vice versa*. In order to test the risks separately and jointly, we simulated the management scenarios under drought risk and/or windstorm risk.

All of these combinations [2 baselines in past climate + (4 scenarios × 2 RCP x (drought risk + windstorm risk + drought and windstorm risks)] yielded a total of 26 scenarios tested.

2.2.2. Forest growth simulation and economic analysis

From the forest growth simulation to the economic analysis, we applied the same methodology as the one described in Brèteau-Amores *et al.* (2020). More precisely, we used MATHILDE (Fortin and Manso, 2016) - a distance-independent individual-based model - to simulate forest dynamics under past climate RCP 4.5 and RCP 8.5. For each management scenario listed in Table III.1, forest growth was simulated using the representative fictive stands developed by Brèteau-Amores *et al.* (2020). Since MATHILDE is known to overestimate the mortality of young trees, which leads to inconsistent simulations for even-aged stands younger than 30 years (Fortin and Manso, 2016), we chose to simulate stands from 30 years of age. Each inventory file contained the tree records of 10 plots of 400 m² each. Simulations of scenarios were based on basal area criteria corresponding to the type of management currently applied according to the recommendations of the silviculture guide. MATHILDE is designed to simulate forest growth in a stochastic fashion based on the Monte Carlo technique. It also uses a built-in harvest algorithm to implement the management scenarios. We computed 1000 realizations for each scenario. Each realization represented the mean evolution of the 10 plots that compose the fictive stand. Each growth realization was processed through a carbon accounting tool (CAT, Pichancourt *et al.*,

2018) in order to simulate the resulting carbon balance. The different realizations of forest growth and carbon balance were then analysed in terms of economic benefits. Additional technical details on MATHILDE and CAT are provided in the Supplementary Material Section (B).

We performed an economic comparison of the adaptation strategies using Hartman's land expectation value (LEV) formula. The experimental design (Figure III.1) allowed for the following comparisons:

• LEV 1 *vs*. LEV 3 and LEV 1 *vs*. LEV 7: effect of drought and/or windstorm.

• LEV 3 *vs*. LEV 4 and LEV 7 *vs*. LEV 8: effect of composition diversification strategy.

• LEV 3 *vs*. LEV 5 and LEV 7 *vs*. LEV 9: effect of structure diversification strategy.

• LEV 3 *vs*. LEV 6 and LEV 7 *vs*. LEV 10: effect of composition diversification combined with structure diversification.

Hartman's model makes it possible to evaluate the combined benefits of timber and amenities production, in this case, carbon sequestration. In France, the final harvest usually occurs when the trees have reached a pre-determined diameter or when the stem density reaches the chosen minimum value. These parameters are part of the built-in algorithm of MATHILDE. Given the fact that each realization is associated with a different growth rate, the final cut can be triggered before the theoretical cutting-age T. For instance, if the growth was much faster than expected, the trees reach their target diameter sooner, thus triggering the final cut. Likewise, if the stand was heavily damaged by a windstorm and/or a drought, a low stem density can trigger the final harvest.

To account for varied rotation lengths, we used a modified version of the Hartman LEV formula (Brèteau-Amores *et al.*, 2020). Using Monte Carlo-based stochastic simulations, the expectation of net present value (NPV) was estimated as follows:

$$\hat{E}[NPV(T)] = \frac{1}{B}\sum_{b=1}^{B} NPV\ (\min(H_b, T)) \tag{1}$$

where b is the index of the realizations (so that b = 1, 2,..., B), T *is* the target rotation length, H_b is the date of the final harvest in realization b, which is at best equal to the target T or smaller than T in case of early harvest.

The expectation of LEV was then approximated by computing the so-called double-weighted LEV, which consists of pooling all the realizations of a Monte Carlo simulation and using the mean rotation length for all cases from the second rotation forwards. The double-weighted LEV formula reads as follows:

$$\hat{E}[LEV(T)] = \frac{1}{B}\sum_{b=1}^{B}\left[NPV\ (\min(H_b, T)) + \frac{\hat{E}[NPV(T)]}{(1+r)^{\min(H_b,T)}}\frac{(1+r)^{\bar{H}(T)}}{(1+r)^{\bar{H}(T)}-1}\right] \tag{2}$$

where $\overline{H}(T) = \sum_{b=1}^{B} \min(H_b, T)/B$. In fact, $\overline{H}(T)$ is the mean harvest age for a target rotation length T. If no early harvest was triggered, then $\overline{H}(T) = T$. Otherwise, $\overline{H}(T) < T$.

In this setup, the forest owner maximizes the double-weighted LEV with respect to *H(T)*, *i.e.,* the forest owner is interested in maximizing the financial net return obtained from both timber production and carbon sequestration. Additionally, the infinite horizon used in double-weighted LEV formula allows for comparing different management strategies associated with different rotation lengths (it is assumed that management practices remain the same over time). According to this formula, the forest owner receives a certain gain after the first rotation, then, from the second rotation, the forest owner receives an expected gain based on the mean rotation length $\overline{H}(T)$ (equation 2). Rewards for carbon service are paid each year based on changes in carbon stocks. Harvesting also comes with financial implications in the form of taxes paid by the forest owner. Carbon benefits were computed based on the additional carbon stored in the standing timber, the soil, and the wood products. The release of carbon stored in wood products was not taken into account. We used the following three carbon costs: 28, 54, and 110 EUR/tC (Brèteau-Amores *et al.*, 2020) as they represent the average market price set by the French low-carbon label[13], the current French shadow price, and the floor value of the social cost, respectively. We also considered a null carbon price corresponding to neglected carbon services. Finally, we optimised the LEV as a way to compute the optimal stand age at which the even-aged stand is clear-cut or the LEV equilibrium for uneven-aged stand is reached.

3. Results

3.1. Effect of drought and/or windstorm recurrence on timber volume, carbon sequestration, tree mortality, and LEV

For each scenario, Table III.2 shows the results of our simulations in terms of total timber volume harvested (*i.e.*, timber harvested from both the thinnings and the final cut for even-aged stands), total carbon sequestrated (*i.e.*, carbon sequestrated aboveground, belowground, and in wood products), and mortality indicators (*i.e.*, average yearly mortality rate and dead wood volume).

Timber volume - Our results show that under current conditions, the total timber volume harvested is larger among beech stands (Baseline_B) than it is among oak stands (Baseline_O). The negative effect of drought and/or windstorm risks on the volume of timber harvested can be observed by comparing the baseline (Baseline_B) to the no-adaptation scenario (B_EA). The differences observed between the more optimistic climate scenario (RCP 4.5) and the more pessimistic one (RCP 8.5) show that more frequent drought and/or windstorm recurrences result in a more pronounced reduction in timber volume. Additionally, the impact of drought and/or windstorm events appear to be more severe under RCP 8.5 than it is under RCP 4.5. Finally, our results show a joint effect of drought and windstorm risks on the volume of timber harvested. Indeed, more produced reductions were observed in scenarios combining both types of risks compared to scenarios including one type of risk only.

[13] "Label Bas Carbone".

Table III.2: Effect of drought and/or windstorm risks in terms total timber volume harvested in cubic meters (m³), total carbon sequestrated in tons (tC), average yearly tree mortality rate in percentage (%), and dead wood volume in cubic meters (m³). Baseline (Baseline_B) is indicated in white. For each scenario, gains/increases compared to the baseline are indicated in blue. Losses/decreases are indicated in red.

Scenarios			Volume	Carbon	Mortality	
					m³	%
PAST		Baseline_B	652	219	47	0.69
		Baseline_O	500	194	20	1.13
RCP 4.5	Drought (D)	B_EA	534	189	26	0.62
		Mix50_EA	477	170	14	1.71
		B_UA	703	121	51	0.31
		Mix50_UA	615	99	28	0.95
	Storm (S)	B_EA	528	191	38	0.69
		Mix50_EA	476	169	23	1.72
		B_UA	677	119	68	0.21
		Mix50_UA	602	98	43	0.96
	D+S	B_EA	496	191	45	0.81
		Mix50_EA	453	167	28	1.94
		B_UA	655	119	96	0.42
		Mix50_UA	589	98	56	1.2
RCP 8.5	Drought (D)	B_EA	329	157	16	0.79
		Mix50_EA	360	143	14	1.93
		B_UA	544	109	37	0.41
		Mix50_UA	464	88	23	1.31
	Storm (S)	B_EA	332	155	28	0.75
		Mix50_EA	346	112	54	1.7
		B_UA	502	105	86	0.43
		Mix50_UA	602	98	43	0.96
	D+S	B_EA	304	154	31	1
		Mix50_EA	331	122	56	2.09
		B_UA	479	105	109	0.58
		Mix50_UA	435	85	57	1.28

Legend	
Gain	100%+
	75-100%
	50-75%
	25-50%
	0-25%
Loss	25-0%
	50-25%
	75-50%

Carbon sequestration - Beech stands capture more carbon than oak stands in current conditions. By comparing Baseline_B and B_EA, we can see that drought and/or windstorm risks decrease carbon sequestration. The greater the recurrence of drought and/or windstorm, the higher the decrease of carbon stored. This decrease is higher in RCP 8.5 than it is in RCP 4.5. Most scenarios conducted under drought risk only or under windstorm risk only result in greater carbon sequestration than scenarios conducted under both risks.

Tree mortality - Under current conditions, dead wood volume is lower in oak stands than it is in beech stands, in contrary to average mortality rate, which is lower in beech stands than it is in oak stands. By comparing Baseline_B with B_EA, we can observe that drought and/or windstorm risks increase the average mortality rate (except for drought in RCP 4.5) and decrease the dead wood volume. Regardless of the scenario, the more frequent drought and/or windstorm recurrence increase the average mortality rate. It increases also their dead wood volume, except for scenarios under only drought risk. Higher mortality rates were observed under RCP 8.5 (compared to RCP 4.5) and when examining drought and windstorm risks jointly rather than separately.

Table III.3: Effect of drought and/or windstorm in terms of land expectation value (LEV) expressed in EUR/ha. For each scenario, for four carbon prices (0, 28, 54, and 110 EUR/tC) and two discount rates (2% and 3%) were examined. Baseline is indicated in white. Gains/increases compared to the baseline are indicated in blue. Losses/decreases are indicated in red.

		Carbon price	0		28		54		110	
		Discount rate	2%	3%	2%	3%	2%	3%	2%	3%
PAST		Baseline_B	1670	509	1729	525	1784	542	1902	600
		Baseline_O	6289	2283	6405	2329	6522	2371	6774	2462
RCP 4.5	Drought (D)	B_EA	1259	404	1316	420	1369	435	1484	528
		Mix50_EA	1762	1931	1832	1952	1898	1971	2039	2013
		B_UA	1664	1025	1668	1025	1945	1072	4837	2657
		Mix50_UA	3904	2355	3907	2355	3910	2356	3916	2357
	Storm (S)	B_EA	1170	374	1221	388	1268	401	1371	484
		Mix50_EA	1799	1964	1862	1984	1925	2003	2059	2043
		B_UA	1633	1009	1636	1010	1946	1073	4842	2660
		Mix50_UA	3856	2333	3859	2334	3862	2334	3868	2335
	D+S	B_EA	1182	381	1240	397	1295	413	1412	490
		Mix50_EA	1723	1892	1789	1911	1850	1930	1981	1969
		B_UA	1585	987	1588	987	1986	1095	4919	2702
		Mix50_UA	3758	2286	3761	2286	3764	2286	3770	2287
RCP 8.5	Drought (D)	B_EA	789	304	907	348	1017	389	1253	477
		Mix50_EA	831	313	902	340	976	374	1221	479
		B_UA	1531	978	1532	978	1960	1081	4868	2674
		Mix50_UA	3630	2267	3631	2268	3632	2268	3634	2268
	Storm (S)	B_EA	711	269	791	300	872	330	1046	400
		Mix50_EA	2184	2256	2187	2256	2190	2257	2197	2258
		B_UA	1462	942	1463	943	1983	1093	4914	2699
		Mix50_UA	3935	2377	3938	2377	3941	2377	3947	2378
	D+S	B_EA	717	274	817	312	910	346	1111	421
		Mix50_EA	2125	2224	2132	2226	2138	2228	2152	2231
		B_UA	1398	910	1399	910	2020	1113	4995	2743
		Mix50_UA	3495	2198	3496	2198	3497	2198	3499	2199

Legend	
Gain	100%+
	75-100%
	50-75%
	25-50%
	0-25%
Loss	25-0%
	50-25%
	75-50%

LEV - Table III.3 shows the results of the economic analysis conducted for four carbon prices (0, 28, 54 and 110 EUR/tC) and two discount rates (2% and 3%). A commonly-used method was followed to perform a sensitivity analysis and evaluate the impact of discount rate changes on each tested scenario. The results of this analysis are provided in the Supplementary Material

Section (C). Our results show that, under current conditions, oak stands are associated with higher LEVs than beech stands. The comparison of Baseline_B with Baseline B_EA clearly illustrates the negative effect of drought and/or windstorm on the LEV. Concerning the adaptation scenarios, the greater recurrence of drought decreases the LEV, contrary to the recurrence of windstorm that increases the LEV except for uneven-aged beech stand (B_UA) and low carbon prices (0 and 28 EUR/tC). For most scenarios, more frequent recurrences of both risks decrease the LEV.

3.2. Effect of adaptation strategies on timber volume, carbon sequestration, tree mortality, and LEV

Timber volume - As showed in Table III.2, two strategies - structure diversification (B_UA) and combined diversification (Mix50_UA) – were found to increase the total volume of timber harvested compared to the baseline (B_EA). While composition diversification (Mix50_EA) increases the total volume of timber harvested under the most severe climate scenario (RCP 8.5), it has the opposite effect under the small-temperature increment scenario (RCP 4.5).

Carbon sequestration - The three adaptation strategies resulted in a reduction of carbon sequestration (Table III.2). Relative to B_EA, composition diversification was found to have the least severe impact on reducing carbon sequestration; combined diversification had the greatest impact.

Tree mortality - Compared to the no-adaptation scenario (B_EA), structure diversification is the only adaptation strategy that was found to decrease the average mortality rate (Table III.2). Regarding the dead wood volume, combined diversification has a positive effect in the following conditions: RCP 4.5 and drought risk under RCP 8.5. Both structure diversification and combined diversification increase the dead wood volume.

LEV - All three adaptation scenarios provide a higher LEV compared with B_EA, except for the scenario of composition diversification under drought risk in RCP 8.5 (*i.e.,* maladaptation case) (Table III.3).

3.3. Effect of carbon price and discount rate on LEV

As Table III.3 indicates, the higher the carbon price, the higher the LEV, but the lower the percentage of gain compared to the baseline (B_EA). In addition to this, discount rate and LEV were found to be inversely proportional. The strategy providing the best economic return depends on these two criteria. For a carbon price between 0 and 54 EUR/tC, combined diversification appears to be the best strategy. Composition diversification is the best option under drought and windstorm risks in the more pessimistic climate scenario (RCP 8.5) for a discount rate of 3%. For a carbon price of 110 EUR/tC, the scenario of structure diversification provides the best economic return.

4. Discussion

4.1. Diversification can be an economically effective adaptation strategy to reduce drought- and windstorm-induced risks of forest dieback

Drought and windstorm risks decrease the total volume of timber harvested and carbon sequestration capacity while increasing the average mortality rate (Table III.2). Both risks have positive and negative effects on LEV (Table III.3). The impacts of drought and/or windstorm events can be mitigated by the implementation of adaptation strategies. While timber production increases as a result of structure diversification (B_UA) or combined diversification (Mix50_UA), tree mortality can be reduced when either structure diversification or composition diversification (Mix50_EA) are adopted. This is in line with recent results showing the positive effect of diversification on forest productivity (Forrester, 2014; Dănescu *et al.*, 2016) and resistance to drought and windstorm (Lebourgeois *et al.*, 2013; Mason and Valinger, 2013; Zapater *et al.*, 2013; Hanewinkel *et al.*, 2014). All three adaptation strategies under study increase the LEV, a result that corroborates our first hypothesis. However, they all result to reduce carbon sequestration, which is contrary to the results observed by Kirby and Potvin (2007) and Lange *et al.* (2015), but in line with a more recent study by Brèteau-Amores *et al.* (2020). Nonetheless, this study demonstrates that adaptation strategies, such as structure diversification and composition diversification (or a combination of both), can provide both forest owners and the society with trade-offs between financial balance and carbon balance. For instance, composition diversification results in higher carbon sequestration than the two other strategies, but only provides the best economic return for a discount rate of 3% in the more pessimistic climate scenario (RCP 8.5). Combined diversification provides the best economic return in the more optimistic climate scenario (RCP 4.5), but is the worst option in terms of carbon sequestration. In between, structure diversification requires a high carbon price to provide the best economic return.

4.2. Considering both risks impacts the results and recommendations compared to investigating each risk separately

In Table III.2, we observed that combining drought and windstorm risks has a greater impact on forest growth and/or carbon sequestration, as compared to examining each risk separately. In addition to this, the combination of both risks can have a multiplicative effect when it comes to tree mortality (this effect was not observed for timber production and carbon sequestration). More precisely, the average mortality rate of uneven-aged beech stand (B_UA) doubles under combined drought and windstorm risks in the small-increment temperature scenario (RCP 4.5) for a carbon price of 54 and 110 EUR/tC. In the more severe climate scenario (RCP 8.5), the dead wood volume in mixed stands (Mix50_EA/_UA) and B_UA for a carbon price of 0 and 28 EUR/tC at least doubled. This observation can be explained by the linkage function in the MATHILDE mortality submodel: A windstorm and a drought occurring during the same time interval will result in greater mortality rates compared to two events occurring during two separate time intervals. However, this greater impact on forest growth and/or carbon sequestration does not imply a greater impact on LEV (Table III.3).

Another interesting result was observed under RCP 4.5 when considering one or two risks: the different combinations of risks have no impact on the strategy providing the best economic return (Table III.3). Under RCP 8.5, the effect of composition diversification (Mix50_EA) is unclear when drought risk is examined separately and can be the worst option (*i.e.,* maladaptation). However, composition diversification appears to be an effective adaptation strategy under windstorm risk; it can even be the best strategy when both risks are present. This corroborates our second hypothesis and shows the importance of taking into account several risks under varied climate scenarios. Diversification can also bring co-benefits, for instance, helping forest stands cope with other disturbances. More specifically, diversification may be an interesting option when it comes to fighting against pests and insects (Griess and Knoke, 2011; Jactel *et al.*, 2017): This option should be tested in such analysis.

4.3. Diversifying the stand as well as combining both strategies lead to synergies

From an economic perspective, synergies arise when a combination of adaption strategies results in greater economic return for the forest owner than each strategy separately. We tested this hypothesis through the Pretzsch and Schütze framework (2009). Additional information about the framework and results tables are provided in the Supplementary Material Section (D).

Tables III.D.1 and III.D.2 present the results of the tested presence or absence of synergy for each adaptation strategy in terms of total volume of timber harvested and LEV. Table III.D.1 shows that stand diversification and combining both diversification strategies have a synergistic effect on the total volume of timber harvested. This effect is accentuated under low carbon prices and a frequent recurrence of drought and/or windstorm. Indeed, 50% (110 EUR/tC) to 75% (0 EUR/tC) of the scenarios under the more optimistic climate scenario (RCP 4.5) show synergies. Under the more pessimistic climate scenario (RCP 8.5), synergies were observed in 77% (110 EUR/tC) to 100% (0 EUR/tC) of the scenarios. Table III.D.2 shows varied synergistic effects on the LEV depending on the discount rate. For instance, 5% (1%) to 100% (4%) of the scenarios under RCP 4.5 have synergetic effects, as well as 8% (1%) to 88% (4%) in RCP 8.5. These results corroborate our third hypothesis and can be explained by the complementarity and asynchrony that exist between beech and oak as it relates to both the resource uptake (Zapater *et al.*, 2011) and the tree structure (Jucker *et al.*, 2015). Loreau and de Mazancourt (2008; 2013) showed that the more species are asynchronic, the more the stand is stable in time. However, we can observe that synergies are not equal between RCP 4.5 and RCP 8.5, which suggest that asynchrony related to the need for resources may evolve under a rapidly changing climate.

As already observed by Knoke and Seifert (2008), mixed stands (Mix50_EA/_UA) show a higher economic return than pure stands (B_EA/_UA) under (i) RCP 4.5 for a carbon price of 0 and 28 EUR/Tc and (ii) windstorm and combined risks under RCP 8.5 for a carbon price between 0 and 54 EUR/tC. Higher LEVs were observed among uneven-aged stands (B_UA and Mix50_UA) compared to even-aged stands (B_EA and Mix50_EA) for (i) a carbon price of 110 EUR/tC, (ii) a carbon price of 54 EUR/tC with a discount rate of 2% in RCP 4.5, and (iii) under drought in RCP 8.5. Müller *et al.* (2019) confirm this result. Our results are in accordance with the literature: There is no “one-size-fits-all” pattern. Therefore, the question of the most effective combination and mixture should continue to be investigated (Mina *et al.*, 2018).

4.4. Valorising carbon increases forest value

The introduction of carbon prices into our economic analysis led to increased LEV (Table III.3). This result shows the importance of taking the provision of carbon services when evaluating timber production from an economic standpoint. Our results also show that the strategy providing the best economic return depends on carbon prices. Indeed, structure diversification was found to be the best option under a carbon price of 110 EUR/tC, irrespective of the other parameters. These results corroborate our fourth hypothesis.

Mixed stands may provide other co-benefits such as a higher biodiversity due to a diversified habitat. In addition to this, the complementary vertical rooting patterns between beech and oak (Mason and Valinger, 2013) creates a better anchorage that may help to reduce soil erosion. An extension of our study can be to integrate these other ecosystem services into the modelling.

5. Conclusion

Severe droughts and windstorms affect both forest growth and carbon sequestration. One specificity of our study was to investigate these two risks from an economic perspective. We showed a higher impact on timber production, mortality, and carbon sequestration when both risks are considered jointly instead of separately. Diversification (composition and structure) can be economically effective adaptation strategies when it comes to reducing drought- and windstorm-induced risks. Diversification also leads to some synergies in terms of timber productivity and economic value (LEV). More precisely, structure diversification or a combination of structure and composition diversification strategies increases timber production. Structure diversification or composition diversification tends to decrease tree mortality. Diversification increases the LEV, but decreases carbon sequestration. Trade-offs between the financial balance and the carbon balance can be achieved by evaluating the impact of carbon price, discount rate, and climate scenario. The heterogeneity of our results showed the importance of considering a variety of parameters, climate scenarios, and ecosystem services. Future research on this topic could include exploring other species, provenances, as a means to evaluate the effectiveness of additional diversification strategies. Integrating other ecosystem services and other risks should also improve this analysis.

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Supplementary material

A. Windstorm frequencies computation

To compute windstorm frequencies, we used daily meteorological data from Météo France for the past climate, the RCP 4.5 and the RCP 8.5. Because severe windstorms occur during autumn and winter (Valinger and Fridman, 2011), we considered the maximum daily wind gust at 10 m from September to February for 20 SAFRAN points. We randomly selected these points within the Grand-Est region to integrate spatial variability: 12413; 13127; 13240;1 3251; 13405; 13829;1 4124; 14243; 14252; 14522; 14544; 14846; 14964; 15097; 15125; 15256; 15547; 15824; 15959; 16533. A given year was defined as having an exceptional windstorm when one of the 20 points had a maximum daily wind gust over 40 m/s, which corresponds to the characteristics of severe windstorms such as Lothar in 1999 (Bonnesoeur *et al.*, 2013).

B. MATHILDE and CAT[14]

MATHILDE is a distance-independent individual-based model that simulates forest dynamics (Fortin and Manso, 2016). MATHILDE is fitted to data from a large network of permanent plots measured over the 1958-2007 period. It is designed to simulate even-aged and uneven-aged stands as well as pure and mixed stands of beech and sessile oak in Northern France. More precisely, it predicts tree mortality, the diameter increment of survivors and the recruitment of new trees over five-year growth periods. The model is composed of different sub-models, which are illustrated on Figure III.B.1.

The climate sub-model is fitted to data from SAFRAN model over the 1959-2012 period. It predicts the mean seasonal temperature over a period, depending on the initial year of the period and the occurrence of drought during the period. The growing season temperature is controlled by a parameter driving its increase. This parameter depends on the given climate scenario and changes when a drought or a windstorm occurs during the period.

The mortality sub-model encompasses many explanatory variables such as tree species, diameter at breast height (DBH, 1.3 m in height), basal area of trees with DBH larger than the subject tree as well as the occurrence of drought, windstorm and harvesting (Manso *et al.*, 2015a). The effects of drought and windstorm are the average of those observed over the last 60 years.

The diameter-increment sub-model predicts the increment of a given tree over a period (Manso *et al.*, 2015b). The explanatory variables are tree species, DBH, basal area of trees with DBH larger than the subject tree, plot basal area, harvest occurrence, and mean seasonal temperature during the time interval.

The sub-model of tree recruitment predicts the number of trees that cross the threshold of 7.5 cm for each species. The explanatory variables are the all-species basal area as well as the basal area of the species. In addition to the aforementioned sub-models, MATHILDE also includes a model of height-diameter relationships (Fortin *et al.,* 2019).

[14] Text similar to Brèteau-Amores *et al.* (2020).

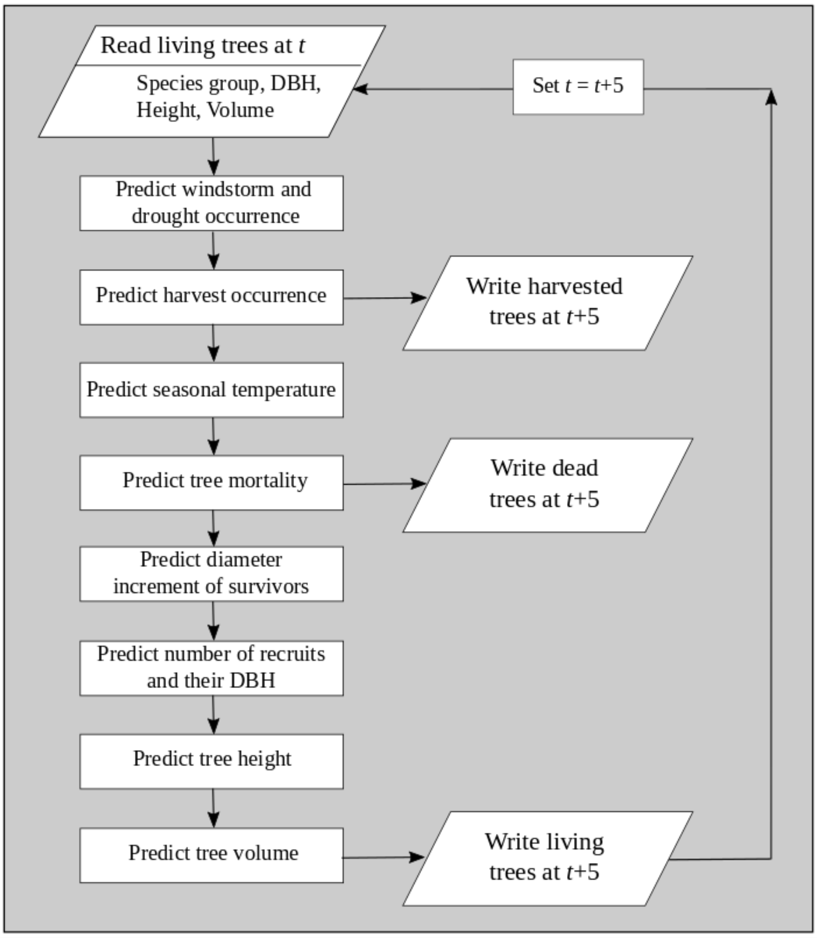

Figure III.B.1: Flowchart of the sub-models composing MATHILDE.

Table III.B.2: Basal area bounds (m^2/ha) that were used in the different management scenarios (source: CRPF[15]). The bounds are age dependent for even-aged management scenarios. n/a: not applicable.

Management scenario	Stand age (years)	Bounds (m^2/ha)
Even-aged beech	0-50	[14, 18]
	50-70	[18, 22]
	70 until final cut	[22, 26]
Even-aged oak	0-50	[14, 18]
	50 until final cut	[18, 22]
Even-aged mixed stand	0-50	[14, 18]
	50 until final cut	[18, 22]
Uneven-aged beech	n/a	[14, 18]
Uneven-aged oak	n/a	[12, 16]
Uneven-aged mixed stand	n/a	[12, 16]

15 Regional Center for Privately-Owned Forests.

MATHILDE is designed to simulated forest growth from inventory data in a stochastic manner using the Monte Carlo technique. This method provides a prediction of the stand evolution as well as the uncertainty associated with this prediction. Confidence interval bounds are derived using the percentile rank method (Efron and Tibshirani, 1993). The model implements an algorithm that triggers the harvesting based on plot basal area and a target dominant diameter, *i.e.,* the mean diameter of the 100 thickest trees per hectare. Once the harvesting is triggered, a sub-model of tree harvest predicts the probability that an individual tree is harvested (see Manso *et al.*, 2018). The management scenarios is implement using MATHILDE's built-in harvest algorithm based on bounds of basal area. Whenever the upper bound is crossed, the harvesting is triggered and the trees are harvesting until the lower bound is reached. The bounds were assumed to reproduce the management of even-aged and uneven-aged stands and are shown in Table III.B.2.

MATHILDE is implemented in the CAPSIS platform (Dufour-Kowalski *et al.*, 2012), which contains a carbon accounting tool (CAT, Pichancourt *et al.*, 2018). CAT allows for the representation of complex emission life cycles inherent to managed forests. It takes into account the main issues related to carbon accounting tools, such as the numerous uncertainties, risk of carbon leakage and double counting. The assessment of the carbon balance is also supported by built-in Monte Carlo error propagation methods. In addition to the IPCC standards, CAT also provides estimates of

(i) cumulative material and energy substitution, that is the greenhouse gas emissions avoided when a harvested wood product (HWP) replaces an alternative product;

(ii) cumulative fossil fuel carbon emissions during the life cycle of the different HWP;

(iii) the accumulation of non-degradable HWP at solid waste disposal site (SWDS), and

(iv) cumulative methane (CH_4) emissions caused by the degradation of HWP at SWDS. By default (semi-aerobic conditions), CAT assumes that 25% of the carbon emitted from the SWDS is methane. The non-degradable part of carbon that accumulates at a SWDS is assumed to be permanently sequestered.

Simulations are run by default under global warming potential factors of the fifth assessment report on climate change (IPCC, 2013). Results are exported in carbon units with the probability level of the confidence intervals equal to 0.95 by default.

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C. Sensitivity analysis of the discount rate on LEV

Table III.C.1: Land expectation value in EUR/ha of each scenario for four carbon prices (0, 28, 54 and 110 EUR/tC) and four discount rates (1, 2, 3 and 4%).

		Carbon price	0				28				54				110			
		Discount rate	0.01	0.02	0.03	0.04	0.01	0.02	0.03	0.04	0.01	0.02	0.03	0.04	0.01	0.02	0.03	0.04
PAST		Baseline_B	7042	1670	509	176	7309	1729	525	185	7557	1784	542	194	8092	1902	600	223
		Baseline_O	23515	6289	2283	900	23515	6405	2329	917	24022	6522	2371	934	24578	6774	2462	969
RCP 4.5	Drought (D)	B_EA	5491	1259	404	143	5586	1316	420	159	5674	1369	435	178	5948	1484	528	218
		Mix50_EA	1129	1762	1931	1980	1322	1832	1952	1987	1569	1898	1971	1993	2152	2039	2013	2006
		B_UA	2502	1664	1025	642	2534	1668	1025	642	4664	1945	1072	660	11647	4837	2657	1629
		Mix50_UA	6611	3904	2355	1459	6643	3907	2355	1459	6673	3910	2356	1459	6815	3916	2357	1459
	Storm (S)	B_EA	4934	1170	374	132	5022	1221	388	147	5103	1268	401	163	5531	1371	484	198
		Mix50_EA	1188	1799	1964	2013	1358	1862	1984	2020	1580	1925	2003	2026	2130	2059	2043	2038
		B_UA	2424	1633	1009	634	2457	1636	1010	634	4666	1946	1073	660	11658	4842	2660	1631
		Mix50_UA	6476	3856	2333	1449	6507	3859	2334	1449	6536	3862	2334	1449	6665	3868	2335	1449
	D+S	B_EA	5092	1182	381	134	5200	1240	397	148	5301	1295	413	165	5619	1412	490	203
		Mix50_EA	1046	1723	1892	1941	1247	1789	1911	1947	1494	1850	1930	1953	2034	1981	1969	1965
		B_UA	2297	1585	987	622	2328	1588	987	622	4763	1986	1095	674	11843	4919	2702	1656
		Mix50_UA	6208	3758	2286	1424	6238	3761	2286	1424	6267	3764	2286	1424	6328	3770	2287	1424
RCP 8.5	Drought (D)	B_EA	2607	789	304	127	3011	907	348	145	3385	1017	389	161	4192	1253	477	205
		Mix50_EA	2784	831	313	129	3030	902	340	141	3300	976	374	160	3967	1221	479	204
		B_UA	2027	1531	978	623	2037	1532	978	623	4700	1960	1081	665	11720	4868	2674	1639
		Mix50_UA	5482	3630	2267	1430	5492	3631	2268	1430	5502	3632	2268	1430	5888	3634	2268	1430
	Storm (S)	B_EA	2398	711	269	111	2667	791	300	124	2934	872	330	135	3543	1046	400	190
		Mix50_EA	1753	2184	2256	2270	1772	2187	2256	2270	1789	2190	2257	2270	1825	2197	2258	2270
		B_UA	1865	1462	942	604	1875	1463	943	604	4755	1983	1093	673	11831	4914	2699	1655
		Mix50_UA	6657	3935	2377	1474	6689	3938	2377	1474	6717	3941	2377	1474	6949	3947	2378	1474
	D+S	B_EA	2384	717	274	116	2726	817	312	131	3045	910	346	145	3730	1111	421	182
		Mix50_EA	1699	2125	2224	2248	1719	2132	2226	2248	1737	2138	2228	2249	1777	2152	2231	2249
		B_UA	1717	1398	910	586	1726	1399	910	586	4845	2020	1113	685	12028	4995	2743	1682
		Mix50_UA	5135	3495	2198	1391	5146	3496	2198	1391	5156	3497	2198	1391	5285	3499	2199	1391

D. Synergy analysis of adaptation strategies[16]

First, the overyielding is defined as a higher observed parameter P_{mix} in the mixed stand than the expected parameter $\widehat{P_{mix}}$ (Pretzsch and Schütze, 2009), *i.e.*,

$$P_{mix} > \widehat{P_{mix}} \leftrightarrow P_{mix} > q_1.P_1 + q_2.P_2$$

where q_1 and q_2 are the respective mixing proportions of species 1 and species 2, and P_1 and P_2 the respective parameter of species 1 and species 2 in monoculture.

Then, a transgressive overyielding of the mixed stand can be observed, when the observed parameter P_{mix} is higher than the parameter of both species in monoculture (P_1 and P_2) (Pretzsch and Schütze, 2009), *i.e.*,

$$P_{mix} > P_1 \text{ and } P_{mix} > P_2$$

The tested parameters were the total harvested timber volume and the land expectation value. The results are presented in Tables III.D.1 and III.D.2. An overyielding is represented by a coefficient of 1 and a transgressive overyielding by a coefficient of 1+. An absence of overyielding is represented by a coefficient of 0.

Table III.D.1: Results of the tested synergy of mixed stands in total harvested timber volume characterised by overyielding (coefficient 1) or transgressive overyielding (coefficient 1+) or absence (coefficient 0) for each scenario and considering four discount rates (1, 2, 3, and 4%).

		Carbon price	0				28				54				110			
		Discount rate	0.01	0.02	0.03	0.04	0.01	0.02	0.03	0.04	0.01	0.02	0.03	0.04	0.01	0.02	0.03	0.04
RCP 4.5	Drought (D)	Mix50	0	0	0	1	0	0	0	1+	0	0	0	1+	0	0	1+	1+
		B_FI	1+	1+	1+	1+	1+	1+	1+	1+	0	0	0	0	0	0	0	0
		Mix50_FI	1	1	1	1	1	1	1	1	1+	1+	1+	1+	1+	1+	1+	1+
	Storm (S)	Mix50	0	0	1	1	0	0	1	1+	0	0	1	1+	0	0	1+	1+
		B_FI	1+	1+	1+	1+	1+	1+	1+	1+	0	0	0	0	0	0	0	0
		Mix50_FI	1	1	1	1	1	1	1	1	1+	1+	1+	1+	1+	1+	1+	1+
	D+S	Mix50	1	0	0	1	0	0	1	1+	0	0	1	1+	0	0	1+	1+
		B_FI	1+	1+	1+	1+	1+	1+	1+	1+	0	0	0	0	0	0	0	0
		Mix50_FI	1	1	1	1+	1	1	1	1+	1+	1+	1+	1+	1+	1+	1+	1+
RCP 8.5	Drought (D)	Mix50	1+	1+	1+	1+	1+	1+	1+	0	1+	1+	0	0	0	0	0	1
		B_FI	1+	1+	1+	1+	1+	1+	1+	1+	0	0	0	0	0	0	0	1
		Mix50_FI	1	1	1	1	1	1	1	1	1+	1	1	1	1+	1	1	1
	Storm (S)	Mix50	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+
		B_FI	1+	1+	1+	1+	1+	1+	1+	1+	1	1	1	1	0	0	1	1+
		Mix50_FI	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+
	D+S	Mix50	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+
		B_FI	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+	1+
		Mix50_FI	1	1	1	1+	1	1	1	1+	1+	1+	1+	1+	1+	1+	1+	1+

[16] Text similar to Brèteau-Amores *et al.* (2020).

Table III.D.2: Results of the tested synergy of mixed stand on land expectation value with a carbon price of 0, 28, 54, and 110 EUR/tC, characterised by overyielding (coefficient 1) or transgressive overyielding (coefficient 1+) or absence (coefficient 0) for each scenario and considering four discount rates (1, 2, 3, and 4%).

		Carbon price	0.01				0.02				0.03				0.04			
		Discount rate	0	28	54	110	0	28	54	110	0	28	54	110	0	28	54	110
RCP 4.5	Drought (D)	Mix50	0	0	0	0	0	0	0	0	1	1	1	1	1+	1+	1+	1+
		B_FI	0	0	0	0	0	0	0	1	1	1	1	1+	1	1	1	1+
		Mix50_FI	0	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1
	Storm (S)	Mix50	0	0	0	0	0	0	0	0	1	1	1	1	1+	1+	1+	1+
		B_FI	0	0	0	1	0	0	0	1	1	1	1	1+	1	1	1	1+
		Mix50_FI	0	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1
	D+S	Mix50	0	0	0	0	0	0	0	0	1	1	1	1	1+	1+	1+	1+
		B_FI	0	0	0	1	0	0	0	1	1	1	1	1+	1	1	1	1+
		Mix50_FI	0	0	0	0	0	0	0	0	1	1	1	1	1	1+	1+	1+
RCP 8.5	Drought (D)	Mix50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		B_FI	0	0	0	1	0	0	0	1	1	1	1	1+	1	1	1	1+
		Mix50_FI	0	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1
	Storm (S)	Mix50	0	0	0	0	0	0	0	0	1+	1+	1+	1+	1+	1+	1+	1+
		B_FI	0	0	0	1	1	0	1	1+	1	1	1	1+	1+	1+	1+	1+
		Mix50_FI	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	D+S	Mix50	0	0	0	0	0	0	0	0	1+	1+	1+	1+	1+	1+	1+	1+
		B_FI	0	0	0	1	0	0	1	1	1	1	1	1+	1	1	1	1+
		Mix50_FI	0	0	0	0	1	1	1	0	1	1	1	1	1+	1+	1+	1+

Chapter IV

Index insurance for coping with drought-induced risk of production losses in French forests

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Abstract

Drought-induced risk of forest dieback is increasing due to climate change. Insurance can be a good option to compensate potential financial losses associated with forest production losses. In this context, we developed an *ex ante* index-based insurance model to cope with drought-induced risk of forest dieback. We applied this model to beech and oak forests in France. We defined and then compared different indices from simple ones relying on rainfall indices to more complex ones relying on the functional modelling of forest sensitivity to water stress. After the calibration of the contract parameters, an insurance scheme was optimized and tested. We showed that optimal insurance contracts generate low gain of certain equivalent income, high compensation, and a high basis risk. The best contract was not proportional to the complexity of the index. There was no clear advantage to differentiate contracts based on species. Results highlighting the various perspectives of this first approach are discussed at the end of this chapter.

Keywords: Drought; Forest; Index insurance.

1. Introduction

In Europe, climate change increases temperature and reduces precipitation, thus accentuating drought-induced risks of forest dieback (Bréda and Badeau, 2008). The exceptional drought of 2003 was associated with a heat wave that severely damaged the French forests (Bréda *et al.*, 2006). The subsequent drought episode (2018) was even stronger in terms of intensity and area impacted (Buras *et al.*, 2020). Forest damages due to extreme drought events include reduced growth, defoliation, and mortality. Loss in timber production may have substantial socio-economic impacts on forest owners. In response, Fuhrer *et al.* (2006) recommended that adaptive management strategies be implemented and that new forest insurance products be developed.

Several management-based adaptation strategies are recommended in order to improve the water consumption efficiency of forest stands and, as a result, their resistance to drought risk. Reduction of density, reduction of rotation length, substitution by a better-adapted tree species, and stand diversification are among the most known adaptation strategies (Spittlehouse and Stewart, 2003).

Another strategy consists of designing risk-sharing strategies through insurance products. In a context of international agreements encouraging countries to protect their forests against the effects of climate change, recommendations have been made to use insurance as a vehicle to finance climate resilience and adaptation. Such recommendations were discussed by the Global Agenda Council on Climate Change (2014), the Organisation for Economic Cooperation and Development (2015), the United Nations Framework Convention on Climate Change (Article 4.8 of UNFCCC), and the Kyoto Protocol (Article 3.14). In exchange for the payment of an annual insurance premium, the forest owner receives an indemnity in case a disaster occurs. In many countries (*e.g.*, China, New-Zealand, USA, Germany, France, Portugal, Spain), forest insurances covering natural disasters have been developed (Brunette *et al.*, 2015). Worldwide, the most common (and first) insurance contract covers the risks of forest fires. However, the adoption of insurance is very different from one country to another. In France, insurers currently sell contracts compensating forest owners for fire and/or storm damage. However, only 2% of the French private forest owners are insured. It is estimated that only 4% of the French forested area is insured (Dossier Sylvassur, 2013). Very low penetration rates also characterize the German, Spanish, and Slovakian markets. In countries like Denmark and Sweden, forest insurance against storm is a much more common practice with 68% and 90% of the private forest owners being insured (Brunette and Couture, 2008). Loisel *et al.* (2020) suggested several explanations accounting for these differences: mandatory insurance (*e.g.*, Norway) *vs*. voluntary insurance (*e.g.*, France), conditional public assistance (*e.g.*, Denmark) *vs*. non-conditional assistance (*e.g.*, France, Germany), objective of timber production in Northern countries *vs*. provision of non-market goods and services in France.

However, to our knowledge, no forest insurance contract offers to cover drought-induced risk of forest dieback. Traditionally, in the agricultural sector, drought is insured through an index-based insurance. However, because of climate change, drought has becomes a significant threat for the forest sector. Index insurance seems to be a relevant and well-adapted tool for forest, since the index can be defined for varied natural hazards and stress levels, such as extreme drought events. In this context, the objective of this paper is to develop and test an index-based insurance specifically designed to help forest owners to cope with drought-induced risk of forest dieback. To this end, we developed an *ex ante* index-based insurance contract and simulated its effectiveness in terms of income smoothing capacity. We simulated the annual forest productivity for two widespread broadleaf tree species in France, beech and oak, by using the CASTANEA forest growth model. This model relies on historical climate series (1960-2015) developed by the SAFRAN reanalysis system (Vidal *et al.*, 2010). We defined and compared different indices from the most simple ones, based on cumulative rainfall indices and the standardized precipitation index (SPI), to more complex ones based on water stress levels, the soil water stress index (SWS) (Guillemot *et al.*, 2017). A series of simulations was performed to calibrate the insurance contract. Then, an optimal insurance scheme was optimized and tested. We showed that optimal insurance contracts generate low gain of certain equivalent income (CEI) and a high basis risk, and compensate a high part of losses. The best contract is not proportional to the complexity of the index. Finally, our preliminary results indicate that there is no clear advantage of differentiating contracts based on species.

The rest of the paper is structured as follows. The next section reviews relevant studies on forest insurance and agricultural index-based insurance. The material and the methods are presented in Section 3. Section 4 provides the results, which are discussed in Section 5. Section 6 concludes.

2. Literature review

This study is at the junction of two research fields: One focusing on forest insurance with no special consideration for index-based insurance, and another one focusing on index-based insurance with no special consideration for the forest sector.

The literature on forest insurance covers a wide range of research topics. One topic deals with actuarial approaches that aim at determining insurance premiums, using different pricing methods. Holecy and Hanewinkel (2006) were the first researchers to propose an actuarial model serving as a basis for the calculation of premiums to cover the German forest for either single or cumulative damaging factors. They proposed a minimum gross insurance premium of 0.77 EUR/ha at age 0 for an insured area of 140,000 ha and a maximum premium of 4429 EUR/ha at age 70 for an insured area of 14 ha. This study highlighted the important role played by the age of the stand and the total insured area in the calculation of the premiums. Other studies followed with for example Pinheiro and Ribeiro (2013) on forest fire insurance in Portugal, Brunette *et al.* (2015) on forest insurance coverage for multiple natural hazards in Slovakia, and Sacchelli *et al.* (2018) in Italy. One of the main conclusions resulting from this body of literature is the need to increase the insured area (as a way to increase mutualisation and dilute the risk) in order to propose affordable insurance premiums.

Another field of research consists of adapting the classical insurance economics model proposed by Mossin (1968) to forest management issues. Thus, Brunette and Couture (2008) developed a theoretical model to predict insurance demand. This model shows the potential negative impact of *ex post* public compensation after a disaster occurrence on the forest owners' demand for insurance. Brunette *et al.* (2017a) proposed a theoretical "risk and uncertainty" model based on the impact of including adaptation efforts into insurance contracts on insurance demand. They showed that insurance could serve as an effective strategy when it comes to encouraging risk- and uncertainty-averse forest owners to adapt to climate change.

The third body of research deals with the assessment of forest owners' demand for forest insurance products. Brunette *et al.* (2013) were the first to assess French forest owners' willingness to pay (WTP) based on different scenarios regarding public compensation. They observed a negative impact of these compensations on the forest owners' WTP. Subsequent studies were conducted to estimate forest owners' WTP in other countries, including China (Dai *et al.*, 2015; Qin *et al.*, 2016), USA (Deng *et al.*, 2015) and Germany (Sauter *et al.*, 2016). More recently, Brunette *et al.* (2019) analysed both real and hypothetical forest fire insurance choices simultaneously, thus demonstrating that real insurance decisions significantly explains the hypothetical ones. Using an experimental economic approach, they also showed that facing ambiguous risk increases the forest owners' WTP.

Finally, a recent article proposed to extend the classical forest economic model setting, the Faustmann optimal rotation model (Faustmann, 1849) under risk (Reed, 1984), to insurance coverage. Loisel *et al.* (2020) analysed the impact of the forest owner's insurance decision on forest management under storm risk. Through their analytical model, they showed that as the insurance coverage increases, the rotation length increases independently of the forest owner's risk aversion. They also identified cases where it may be optimal for the forest owner not to purchase an insurance contract. They provided evidence that an *ex ante* public transfer to the insurer, resulting in a reduced insurance premium, might increase insurance demand. Qin *et al.* (2016) observed the same result in China with an *ex ante* public transfer to insured.

With regard to the index-based insurance literature, the principles of insurance based on meteorological indices were initiated by Halcrow (1948) and further developed by Dandekar (1977). These insurance products were initially proposed to help farmers cope with agricultural risks. They were mainly implemented in developing countries (Skees *et al.*, 1999; Mahul, 2001) where limited infrastructures make low transaction costs contracts even more profitable for insurers and more valuable for insured.

Under index-based insurance contracts, farmers pay an annual premium and, in exchange, receive a monetary compensation when the index (calculated based on weather variables) goes beyond a predefined value. In the case of traditional insurance contracts, indemnity payments typically require that an expert observes and assesses the severity of crop damage after a disaster. This process induces an additional cost resulting in higher insurance premium and introduces asymmetry of information between the insurer and the insured farmer. In the case of index-based insurance, neither the principal (the insurance company) nor its agent (the insured) have control over the meteorological data that are used to define the index. An observable index built upon meteorological data solves any moral hazard issue (Goodwin and Mahul, 2004), reduces transaction costs, and allows for a quick payment of the indemnity (Alderman and Haque, 2007). Moreover, indices allow for focusing on one risk independently of other conditions. Having a single index for a same given disaster and many contracts (and not for a specified risk and for a specific stand) also reduces the transaction costs and, thus, the insurance premium.

However, the main limitations of index-based contracts stem from the imperfect nature of the index itself. Basis risk may become a concern when there are mismatches between income and index realisation) (Skees, 2003). The two types of basis risk are (i) when forest owners receive an indemnity while they did not endure losses (type I), and (ii) when forest owners endure losses without receiving an indemnity (type II). Imperfect insurance products characterized by high basis risk are typically associated with very low consumer demand (Clement *et al.*, 2018). The readability of the contract and simplicity of the index is also a challenge when it comes to advertising and selling such contracts. Keeping in these considerations in mind, one of the objectives of our study is to develop and test multiple, increasingly complex indices.

We thus propose a new method, based on an *ex ante* index-based insurance, for coping with an increasing risk in forest, drought-induced risk of dieback. To our knowledge, this is the first study that (i) deals with drought insurance for forest; (ii) proposes an index-based insurance to cope with forest disturbances; and (iii) investigates the optimal forest insurance contract in France. Our objective is to expand the existing knowledge on one of the above-described research domains, *i.e.*, actuarial approach, by simulating data to compute insurance premiums and optimal insurance contracts through an innovative method. We examined varied stand ages, the same way Holecy and Hanewinkel (2006) did in their study.

3. Material and methods

3.1. Data

Due to the lack of historical data about locally observed annual forest growth, we simulated a series of annual productivity for two widespread broadleaf tree species in France, beech and oak, using the CASTANEA model.

CASTANEA is a mechanistic model simulating the functioning of the main managed European tree species (Davi *et al.*, 2005; Dufrêne *et al.*, 2005; Cheaib *et al.*, 2012; Guillemot *et al.*, 2017). It provides data on the evolution of water and carbon fluxes and stocks (both aboveground and belowground) of the forest ecosystem, with processes simulated at time intervals ranging from half an hour (photosynthesis) to a day (biomass growth). More precisely, CASTANEA simulates photosynthesis and respiration to estimate net forest productivity and in-turn forest growth through biomass allocation rules. CASTANEA takes the specificity of each species into account and includes some physiological responses to drought, such as the risk of decreased growth and mortality resulting from water stress and shortage of carbohydrate reserves (Davi and Cailleret, 2017).

CASTANEA requires weather data (*e.g.*, global or photosynthetically active radiation, air temperature, relative air humidity, wind speed, precipitation) as inputs. We used gridded data produced by the Météo France reanalysis system (SAFRAN) for the reference climate (1960-2015). These data are available for the whole metropolitan France territory divided into 8588 pixels of 8×8 km each. Following Cheaib *et al.* (2012), distributions of available water contents were extracted from the French soil database developed by the INRAE [1 : 10 000 000-scale, Infosol Unit, INRAE, Orléans, (Jamagne *et al.,* 1995)] and aggregated to the 8-km climate grid in order to provide measures of available water capacity and soil depth (Badeau *et al.,* 2010).

In order to capture the climatic variability exclusively, the plot age was kept constant along the 1960-2015 simulations, as well as the biomass (reinitialised to their initial value each year). We thus simulated forest growth for three different classes of stand age linked to an initial biomass in gC/m^2, in order to consider age and biomass variability. Three pairs of age-biomass (year-gC/m^2) were considered: 40-5000, 70-7000 and 100-9000. The annual output data, *i.e.*, productivity, was expressed in terms of volume of wood in m^3/ha or carbon in gC/m^2.

Finally, in order to compute the annual income based on annual productivity, we used a series of annual average wood prices made available by the *Comptes de la Forêt* of the Observatory for Forest Economics (OLEF, BETA), France. We used wood prices for beech and oak and for a diameter class of 71-80 cm corresponding to the commercial timber class. Following the severe damage caused by the Lothar storm of 1999, the decrease in wood value was such that prices were not recorded for the following year. We handled the missing data by computing wood prices using the discounted prices set by the French National Forest Office (ONF), *i.e.*, 85% off for oak and 50% off for beech.

3.2. Insurance policy design

We started with a simple framework with the following assumptions: (i) The representative agent is a private forest owner whose aim is to reduce the effect of drought risk on their stand; (ii) a private insurer offers the same contract to all representative agents, regardless of their location on the French territory; and (iii) each SAFRAN point represents the stand of an agent. In order to compare the gain in certain equivalent income (CEI), the utility with and without insurance was computed for each agent. The agent purchases an insurance contract as long as the gain of CEI is positive.

3.2.1. Indemnity schedule

Indemnity schedule was defined by three parameters according to the framework designed by Vedenov and Barnett (2004). The strike S is the threshold level of the index that triggers payoffs for insured forest owners. The slope-related parameter λ ($0 < \lambda < 1$) determines the exit level ($\lambda.S$) from which payoffs are capped to a maximum M. All these elements are illustrated on Figure IV.1.

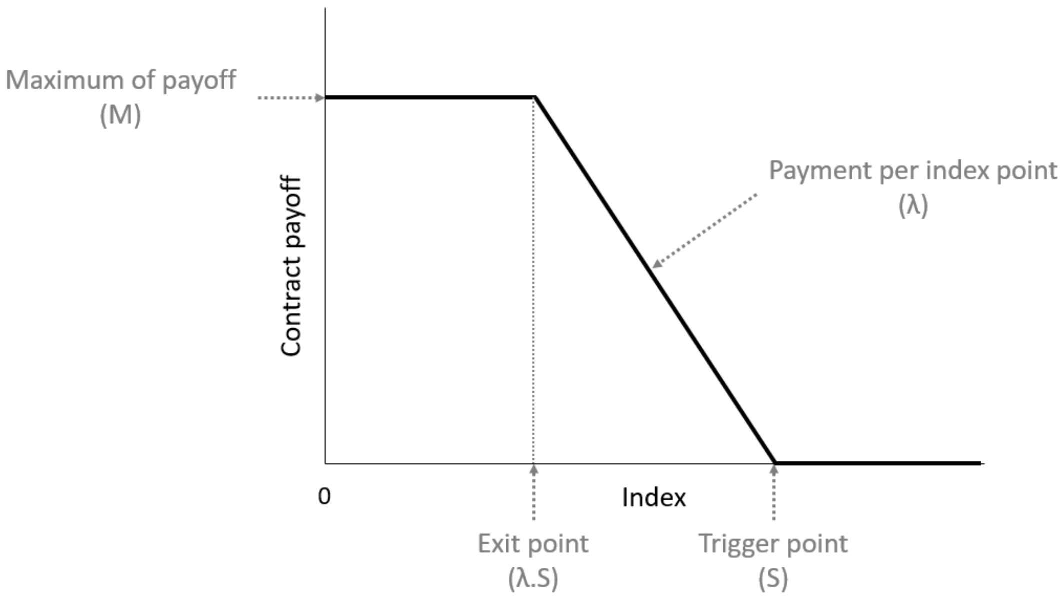

Figure IV.1: Payoff structure of an index-insurance contract (adapted from Vedenov and Barnett, 2004).

We thus have the following indemnity function depending on x, the observed level of the index:

$$i(S,\lambda,M,x)=\begin{cases} M & if\ x\ \leq\ \lambda.S \\ \dfrac{S-x}{S-\ \lambda.S} & if\ \lambda.S<x\leq S \\ 0 & if\ x>S \end{cases} \tag{1}$$

3.2.2. Tested indices

To assess the interest of an index, we defined, tested, and compared different indices from the most simple ones (*i.e.*, basic rainfall index) to more complex ones (*i.e.*, drought index).

The first index is based on the cumulative precipitation during the growing season. We tested two types of cumulative rainfall: The three months cumulative precipitation (CP3) from June to August where the lack of water is the highest and the six months cumulative precipitation (CP6) from April to September, which corresponds to the entire growing period.

The second index is the standardized precipitation index (SPI), which represents a slight improvement over the cumulative precipitation and is widely used to characterise meteorological drought. SPI quantifies observed precipitation as a standardized departure from the mean of the considered period. We computed the three-month SPI (SPI3) and the six-month SPI (SPI6) using the same time period as the one used for the computation of CP3 and CP6, respectively. However, while the SPI measures water supply, it does not take into consideration evapotranspiration, and thus, does not account for the effect of temperature on moisture demand and availability.

We therefore considered a more complex index, namely, the integrated annual soil water stress index (SWS) (Guillemot *et al.*, 2017), which takes into account water supply (rainfall and soil water capacity) as well as water demand (canopy and soil evapotranspiration). The index also considers some vegetation characteristics such as the water stress impact on the stomatal[17] closure. The rationale for considering the SWS index is that forest productivity depends on the availability of soil water to support tree growth. Indeed, soil water content has been shown to have low effects on plant metabolism up to a certain threshold (Granier *et al.,* 1999). To replicate the conditions under which trees start regulating water consumption in order to grow and survive, we applied a 40% threshold on the available water content in the soil (AWC) (Lebourgeois *et al.*, 2005). The annual SWS index, which represents the sum of all water stress occurrences observed during the growing season (*i.e.,* 200 days), is computed by CASTANEA model as follows:

$$SWS_y=\sum_{d=d_{budburst}}^{LS}\max\left(0,\min\left(1,\frac{SWC_d-SWC_{wilt}}{0.4(SWC_{fc}-SWC_{wilt})}\right)\right) \tag{2}$$

[17] *Stomatae* are small apertures on leave surface where water and CO_2 exchanges between tree and air take place.

where SWS_y is the soil water stress index of year y (unitless), $d_{budburst}$ is the day of budburst, LS is the day of leaf senescence, SWC_d is the soil water content on day d (mm), SWC_{wilt} is the soil water content at the wilting point, *i.e.,* the minimum amount of water in the soil that the plant requires not to wilt (mm), and SWC_{fc} is the soil water content at field capacity, *i.e.,* the maximum water retention capacity of the soil (mm). The *SWS* is computed for each species: SWS_{beech} and SWS_{oak}.

The Vedenov and Barnett (2004) model was based on an index of water availability in the soil, where the indemnity increases when the index decreases (up to the floor value) and the index is always greater than zero. According to this model, we transformed the SPI and SWS values. The range of SPI was changed from [-5; +5.5] to [0; 10.5] as a way to have positive values only. The range of values of SWS was kept the same; *i.e.*, [0; 200], but the transformation led to having values close to zero corresponding to the highest level of drought, instead of 200 prior to the transformation. The final range of value is summarised in Table IV.1.

Table IV.1: Minimum, mean, maximum values, and standard deviation of the tested indices.

	Min	**Mean**	**Max**	**Std dev**
CP3	1.7	193.9	1061.8	87.9
CP6	33.5	414.6	1545.5	139.6
SPI3	0	3.9	9.3	1.6
SPI6	0	4.7	10.4	1.9
SWS_{beech}	0	123.0	168.5	28.4
SWS_{oak}	0	125.4	172.7	29.1

3.2.3. Optimisation of insurance contract

First, we computed the income without insurance (W_0) and with insurance (W_{ins}) as follows:

$$W_0(t) = K_0 + w(t) \tag{3}$$

$$W_{ins}(t) = K_0 + w(t) + i(t) - p, \qquad with\ p = \sum_{t=0}^{T}\left(\frac{i(t)}{N/_T}.(1+\tau)\right) \tag{4}$$

where K_o stands for the initial non-timber capital of the agent, w is the income from timber production of year t and i the indemnity of the year t. p is the annual premium, N the number of agents, T the time period and τ the loading factor, which represents administrative costs as well as the cost of the risk taken by the insurer (we assume an actuarially fair insurance, *i.e.,* τ = 0).

For the majority of French private forest owners, timber production is not their principal economic activity. Due to the lack of data, we approximated the initial non-timber capital with the average income of a rotation, *i.e.,* the time between the natural regeneration/plantation to the final harvest of the forest stand.

Second, we used a constant relative risk aversion (CRRA) utility function U to compute the variation of CEI. This function is commonly used in the literature to represent individual insurance behaviours, particularly those of forest owners (Sauter *et al.*, 2016; Brunette *et al.*, 2017b). The utility function and the CEI are computed as follows:

$$\left\{U_0\big(W_0(t)\big) = \frac{W_0(t)^{1-\rho}}{1-\rho} \;\middle|\; U_{ins}(W_{ins}(t)) = \frac{W_{ins}(t)^{1-\rho}}{1-\rho}\right\} \tag{5}$$

$$\left\{CEI(\overline{W_0}) = \left[(1-\rho).EU(\overline{W_0})\right]^{\frac{1}{1-\rho}} \;\middle|\; CEI(\overline{W_{ins}}) = \left[(1-\rho).EU(\overline{W_{ins}})\right]^{\frac{1}{1-\rho}}\right\} \tag{6}$$

where $EU(\overline{W}_0)$ the expected utility of the vector of income realizations $(\overline{W_0})$ without insurance, $EU(\overline{W}_{ins})$ the expected utility of the vector of income realizations $(\overline{W_{ins}})$ with insurance, and ρ the relative risk aversion coefficient as defined by Arrow-Pratt.

Finally, we optimised the contract parameters (S, λ, M) in order to maximise the CEI for each index. Rothschild and Stiglitz (1976) demonstrated that the differentiated contracts could reduce the asymmetry of information, in particular the adverse selection, compared to a unique contract. In order to assess the possibility of differentiating insurance contracts by species, we computed the optimal insurance contract for a baseline corresponding to a unique contract, and one for each species separately (beech and oak).

4. Results

Table IV.2 shows the parameters of the optimal insurance contract (S, λ, M), the gain of CEI with insurance (CEI_{ins}) compared to the initial one (CEI_0), and the annual premium for the baseline (unique insurance contract) and the species-specific contracts for each tested index for the age-biomass class of 70-7000. The results for the two others classes are available in the Supplementary Material Section (A). The results are presented for a relative risk aversion coefficient of 1 corresponding to the estimated coefficient of French private forest owners (Brunette *et al.*, 2017b). Table IV.2 shows that all contracts are different from each other depending on the considered indices, the age-biomass classes, and/or the species. All species-specific contracts are different from the unique contract (baseline). The contract maximising CEI is provided by SWS regarding the age-biomass class and the relative risk aversion coefficient. We can see that gain in CEI are very low. Gain in CEI decreases with the type II basis risk.

To assess the interest of an index and compare them, we computed three criteria. The first one is the part of financial losses compensated by indemnity. The second criterion is the part of basis risk, type I and type II. The last criterion is the part of real losses that are compensated, *i.e.,* the number of cases when the index perfectly matches the loss of income. The results of these three criteria are presented in Table IV.3 for a relative risk aversion coefficient of 1 and for the age-biomass class of 70-7000. The results for the two others classes are available in the Supplementary Material Section (A). Moreover, while we assume a constant relative risk aversion equals to 1, a sensitivity analysis of this coefficient was performed and is presented in Supplementary Material Section (B for a coefficient of 0.5 and C for a coefficient of 2). Table IV.3 shows the variability in terms of the percentage of loss compensated by indemnity, going from 26.6% (with SWS) to 99.5% (with SPI6). However, we can see that large percentages of loss compensated by indemnity is linked to a high type II basis risk (close to 50% of the cases). Six-month indices (CP6, SPI6) present higher losses compensated, a lower type I basis risk, and a higher type II basis risk than three-month indices (CP3, SPI3). The more complex index, SWS, shows lower losses compensated, a higher type I basis risk, and a lower type II basis risk than the other indices.

Table IV.2: Strike (S), slope-related parameter (λ) and maximum of indemnity (M) of the optimal insurance contract, the percentage of gain of certain equivalent income with insurance ($CEI_{ins,}$, in EUR) compared to the initial one (CEI_0, in EUR), and the annual premium for each index for the baseline in EUR (unique contract) and the species-specific contracts (beech and oak) considering an age-biomass class of 70-7000 and a relative risk aversion coefficient of 1.

Species	Index	CEI_0	CEI_ins	S	λ	M	Gain	Premium
Baseline	CP3	3122.30	3125.94	141.7	0.1	0.5	0.117	67.39
Beech	CP3	2737.89	2740.49	231.7	0	0.3	0.095	119.63
Oak	CP3	3473.27	3477.57	131.7	0.1	0.6	0.124	65.35
Baseline	CP6	3122.30	3124.05	323.5	0	0.6	0.056	43.42
Beech	CP6	2737.89	2739.51	453.5	0.1	0.3	0.059	90.95
Oak	CP6	3473.27	3475.20	293.5	0.4	0.5	0.056	36.57
Baseline	SPI3	3122.30	3123.57	3.1	0	0.3	0.041	45.42
Beech	SPI3	2737.89	2738.76	3	0.2	0.2	0.032	34.40
Oak	SPI3	3473.27	3474.61	3.1	0.1	0.3	0.039	50.46
Baseline	SPI6	3122.30	3122.39	0.6	0.9	0.3	0.003	1.42
Beech	SPI6	2737.89	2738.07	1.3	0.1	0.3	0.007	3.64
Oak	SPI6	3473.27	3473.32	0.6	0.9	0.2	0.002	0.95
Baseline	SWS	3122.30	3130.21	133	0.3	0.6	0.254	170.30
Beech	SWS	2737.89	2745.58	143	0.2	0.6	0.281	201.40
Oak	SWS	3473.27	3480.14	127	0.2	0.7	0.198	139.59

Additionally, we assessed the possibility of differentiating insurance contract by species and the interest of each index. Table IV.4 summarises the results of the comparison between the baseline (unique contract) and the species-specific contracts for the different indices in terms of maximum of gain of CEI and compensated losses, and minimum of premium and basis risk for the three age-biomass classes. Results show that no index provides the best level for all the parameters and all age-biomass classes. There are differences among indices (an index can be advantageous for some criteria and detrimental for other criteria) and age-biomass classes. Only the results in terms of gain and premium are the same among age-biomass classes: SWS provides the best gain and CP6 the worst one; SPI6 provides the lowest premium and SWS the highest one. Focusing on the gain of CEI, there is no value added associated with developing species-specific contracts based on SPI3, regarding age-biomass classes. Except for this case, there is no clear advantage to differentiate contracts by species. Results depend on the considered index, age-biomass class, and criterion.

Table IV.3: Percentage of financial losses compensated by indemnity (Comp_loss), percentage of type I (BR_I) and type II (BR_II) basis risk and percentage of the number of cases corresponding to real losses compensated (Real_loss) for each index for the baseline (unique contract) and the species-specific contracts (beech and oak) considering an age-biomass class of 70-7000 and a relative risk aversion coefficient of 1.

Species	Index	Comp_loss	BR_I	BR_II	Real_loss
Baseline	CP3	76.1	9.6	34.6	19.7
Beech	CP3	75.7	14.5	19.4	58.3
Oak	CP3	65.6	11.1	25.8	13.1
Baseline	CP6	84.6	9.4	37.3	17.0
Beech	CP6	81.5	13.8	23.2	54.5
Oak	CP6	80.8	8.4	29.9	9.1
Baseline	SPI3	83.9	14.0	32.1	22.3
Beech	SPI3	93.0	6.5	50.7	27.1
Oak	SPI3	73.5	19.4	22.0	17.0
Baseline	SPI6	99.5	0.1	54.1	0.2
Beech	SPI6	99.3	0.5	76.0	1.8
Oak	SPI6	99.5	0.1	38.8	0.2
Baseline	SWS	39.7	21.6	15.6	38.8
Beech	SWS	59.1	12.8	17.2	60.6
Oak	SWS	26.6	25.7	13.8	25.2

Table IV.4: Comparison between the baseline and the species-specific contracts for the different indices, for each age-biomass class (40-5000, 70-7000, 100-9000), and for a relative risk aversion coefficient of 1. Letters correspond to species-specific contracts (B for beech and O for oak) that have a higher gain of certain equivalent income (CEI), a higher premium, a higher percentage of financial loss compensated by indemnity (Comp_loss), a lower percentage of type I basis risk (BR_I) and type II basis risk (BR_II), and a higher percentage of the number of cases corresponding to real losses compensated (Real_loss) compared to the baseline. Colours correspond to the comparison of contracts between the different indices for each parameter, going from the contract offering the best level of the parameter (dark green) to the contract offering the worst one (dark orange).

	40_5000					70_7000					100_9000				
	CP3	CP6	SPI3	SPI6	SWS	CP3	CP6	SPI3	SPI6	SWS	CP3	CP6	SPI3	SPI6	SWS
Gain	O	B		B	B	O	B		B	B	B O				
Premium		O	B	O	O	O	O	B	O	O	B O	B O		B O	B O
Comp_loss	B		B		B O			B	O	B	B	B	B	B O	B
BR_I			B		B		O	B		B	B	B O	B	B O	B
BR_II	B O	B O	O	O	O	B O	B O	O	O	O	O	O	O	O	
Real_loss	B	B	B	B	B	B	B	B	B	B			B		B

5. Discussion and perspectives

5.1. Optimal insurance contracts generate low gain, high compensation and a high basis risk

The heterogeneity of optimal insurance contracts shows the importance of testing different indices and considering different parameters (*e.g.*, species, age-biomass, relative risk aversion coefficient) (Table IV.2). However, a common result is the low gain in CEI (Table IV.2). Leblois *et al.* (2014) also demonstrated this result after testing an *ex ante* insurance model for agriculture. Their low gain might be explained by the cost associated with the implementing such insurance policies (Leblois *et al.*, 2014). Here, our low gain are probably the result of a high basis risk (Clement *et al.*, 2018).

SWS provides the best contract for both the baseline (unique contract) and the two species-specific contracts, but with the lowest gain in CEI, the highest premium, and the lowest percentage of loss compensated by indemnity. Additionally, while an index like SPI provided almost full compensation of lost income, this was associated with a large percentage of loss not compensated by an indemnity (type II basis risk) (Table IV.3), which is the worst risk between the two basis risks, because it undermines the credibility and sustainability of the system. The type I basis risk, which can induce a higher premium, was low in our results (Table IV.3). There is a trade-off between having a strong correlation between the index and the losses and having a large percentage of compensated losses. The heterogeneity of our results showed the difficulty of defining a “perfect” index (Table IV.4).

5.2. Including a regional differentiation on the species-specific insurance contract can improve the results

There was no clear advantage to differentiate the contract by species (Table IV.4). However, this study will include some improvements. First, we will include a coniferous species, Norway spruce, in order to add some variability in terms of timber production and drought tolerance.

Second, French insurers typically apply a multiplicative coefficient to the insurance premiums in geographical areas associated with increased risks, *e.g.,* Mediterranean regions for fire risk. They also exclude some regions considered as uninsurable. Based on this idea of spatial heterogeneity towards risk, we will test if there is a spatial correlation of indemnity, such as a North-South limit, to determine risky areas and categories and thus the relevance of categorised contracts. The differentiation of the index level by categories, for example a differentiation by major ecological regions (GRECO), may minimise the basis risk.

5.3. Other perspectives of the study

Our results are based on a first approach that will be improved by taking the following steps.

First, the insurance premium is typically higher than the expected indemnity. Indeed, our insurance model was based on an actuarially fair insurance. The most common insurance economics literature (Mossin, 1968) shows that unfair insurance premium reduces the level of insurance. We can thus expect that applying a loading factor of 10%, as studied by Brunette and Couture (2018) and Loisel *et al.* (2020), will increase insurance premiums and reduce the level of insurance.

Second, insurance contracts could be adapted to the context of increasing risk linked to climate change. This would prevent the price of premiums from increasing over time (resulting in fewer insured on the market), and thus, maintain the viability of the insurance system. Indeed, the system should only give indemnity for high damage but for few cases. The definition of index level for exceptional drought events needs to be flexible and compensate insured owners less frequently but for more severe damages. To test such contracts, we will perform index and insurance contract simulations under different climate change scenarios using a variety of global climate predictive models. We have already collected future climate data (2016-2100) for two different climate change scenarios, namely the representative concentration pathways (RCP) 4.5 and 8.5 (IPCC, 2013). These two scenarios have been downscaled and bias corrected according to the SAFRAN grid used for the simulation presented in a previous study (Fargeon *et al.*, 2020). To account for uncertainties related to the type of climate model, these data were made available for five different combinations of global-regional climate models (Fargeon *et al.*, 2020).

Third, only wood prices for a diameter class of 71-80 cm were used as part of this first approach. The same way we tested different age-biomass classes, we will include three other wood price series (52-60 cm, 60-71 cm, 80 cm and more), corresponding to other classes of commercial timber. We have access to these wood prices series through the *Comptes de la Forêt* of the Observatory for Forest Economics (OLEF, BETA), France.

Four, from a methodological perspective, we will apply out-of-sample estimations and test their impact on basis risks. Indeed, Leblois *et al.* (2014) demonstrated the need for this method as a way to avoid overfitting and thus the over-estimation of the contracts. They also showed how the hypothesis regarding the initial non-timber capital of the agent could affect the results. The robustness of this parameter must be tested.

6. Conclusion

Since 2017, the French public sector is no longer involved in selling insurance products. Insurance contracts are exclusively provided by private insurance companies. The small percentage of insured forest owners shows the need to develop new and suitable insurance products, especially in a context of accelerating climate change. To prepare for increasing drought-induced risk, index-based insurance contracts may provide a valuable risk management tool to compensate forest owners for financial losses.

The innovative aspect of our study was to investigate an *ex ante* index-based insurance model for forest disturbances. We showed that optimal insurance contracts are associated with low gain in CEI and provide high compensation and high basis risk. There was no clear advantage to differentiate contracts by species. However, this result should be investigated further by including a regional differentiation. This preliminary study will be improved, in particular with the inclusion of future climate data.

This study offers several directions for future research pertaining to forest adaptation to climate change. Insurance contracts can serve as incentives for forest owners (Brunette *et al.*, 2017a), especially those who do not sufficiently use silvicultural practices to adapt to climate change (Andersson and Keskitalo, 2018). Lower indemnity (or higher premium) in case of damage may further encourage forest owners to adopt new forest management practices. Another extension of this study could be to integrate the cost of carbon into timber insurance as suggested in some articles (Subak, 2003; Wong and Dutchke, 2003; Figueiredo *et al.*, 2005; Grover *et al.*, 2005). Finally, drought induces long-term damage resulting in severe risk of dieback, which may be associated with secondary risks such as pest attacks (Desprez-Loustau *et al.*, 2006) and fire (Stephens *et al.*, 2018). The complexity of the dieback process can result in a significant misalignment between the index and the stand damage. Working with simulated data, we cannot represent this effect on our results. As soon as observed data will be available, we will have the possibility to test our model using composite indices that are able to handle greater degrees of complexity. Additionally, insurance contracts can be a way to cope with multiple related risks. The development of insurance contracts for dependant risks, such as drought and fire, should be investigated (only insurance contracts for independent risks are currently available: storm and/or fire).

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Supplementary material

A. Optimal insurance contract and effectiveness criteria of the insurance contract (relative risk aversion coefficient of 1)

Table IV.A.1: Strike (S), slope-related parameter (λ) and maximum of indemnity (M) of the optimal insurance contract, the percentage of gain of certain equivalent income with insurance (CEI_{ins}, in EUR) compared to the initial one (CEI_0, in EUR), the annual premium (in EUR), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of type I (BR_I) and type II (BR_II) basis risk and the percentage of the number of cases corresponding to real losses compensated (Real_loss) for each index for the baseline (unique contract) and the species-specific contracts (beech and oak) considering an age-biomass class of 40-5000.

Species	Index	CEI_o	CEI_ins	S	λ	M	Gain	Premium	Comp_loss	BR_I	BR_II	Real_loss
Baseline	CP3	3277.90	3282.08	141.7	0	0.6	0.127	72.82	67.8	11.8	28.6	17.6
Beech	CP3	2797.10	2800.01	231.7	0.1	0.3	0.104	132.88	70.8	17.1	18.2	55.7
Oak	CP3	3720.14	3725.17	131.7	0.2	0.6	0.135	73.31	47.5	13.9	18.4	10.3
Baseline	CP6	3277.90	3279.89	313.5	0	0.7	0.061	43.36	80.8	9.9	32.7	13.5
Beech	CP6	2797.10	2798.89	473.5	0.1	0.3	0.064	103.02	77.4	17.5	18.5	55.4
Oak	CP6	3720.14	3722.37	293.5	0	0.9	0.060	39.61	71.6	10.5	21.7	6.9
Baseline	SPI3	3277.90	3279.35	3.1	0.1	0.3	0.044	50.46	77.7	17.0	26.9	19.3
Beech	SPI3	2797.10	2798.05	3.1	0.2	0.2	0.034	37.79	91.7	8.5	46.1	27.9
Oak	SPI3	3720.14	3721.65	3.1	0.2	0.3	0.041	56.69	59.4	23.5	15.9	12.8
Baseline	SPI6	3277.90	3278.01	0.6	0.9	0.3	0.003	1.42	99.4	0.1	45.9	0.2
Beech	SPI6	2797.10	2797.30	1.3	0.1	0.3	0.007	3.64	99.2	0.6	72.2	1.7
Oak	SPI6	3720.14	3720.20	0.6	0.9	0.2	0.002	0.95	99.3	0.2	28.5	0.2
Baseline	SWS	3277.90	3286.44	131	0	0.9	0.260	176.56	22.0	26.4	13.1	33.1
Beech	SWS	2797.10	2805.09	143	0.2	0.6	0.286	214.55	52.9	16.2	14.4	59.5
Oak	SWS	3720.14	3727.87	124	0.2	0.8	0.208	146.50	104.9	29.3	10.5	18.1

Table IV.A.2: Strike (S), slope-related parameter (λ) and maximum of indemnity (M) of the optimal insurance contract, the percentage of gain of certain equivalent income with insurance (CEI_{ins}, in EUR) compared to the initial one (CEI_0, in EUR), the annual premium (in EUR), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of type I (BR_I) and type II (BR_II) basis risk and the percentage of the number of cases corresponding to real losses compensated (Real_loss) for each index for the baseline (unique contract) and the species-specific contracts (beech and oak) considering an age-biomass class of 100-9000.

Species	Index	CEI_o	CEI_ins	S	λ	M	Gain	Premium	Comp_loss	BR_I	BR_II	Real_loss
Baseline	CP3	2959.58	2962.67	141.7	0	0.5	0.104	60.68	83.0	7.5	42.4	21.9
Beech	CP3	3229.89	3233.47	131.7	0	0.6	0.111	58.84	89.2	2.3	61.6	21.9
Oak	CP3	3229.89	3233.47	131.7	0	0.6	0.111	58.84	77.8	8.2	35.3	15.9
Baseline	CP6	2959.58	2961.09	323.5	0.1	0.5	0.051	40.21	88.7	7.3	45.1	19.2
Beech	CP6	3229.89	3231.51	293.5	0.3	0.5	0.050	31.42	94.3	1.7	67.8	15.7
Oak	CP6	3229.89	3231.51	293.5	0.3	0.5	0.050	31.42	88.1	6.2	40.1	11.2
Baseline	SPI3	2959.58	2960.67	3.1	0	0.3	0.037	45.42	87.3	10.8	38.8	25.5
Beech	SPI3	3229.89	3231.04	3.1	0	0.3	0.036	45.42	91.7	5.3	52.5	31.0
Oak	SPI3	3229.89	3231.04	3.1	0	0.3	0.036	45.42	82.9	14.8	29.7	21.6
Baseline	SPI6	2959.58	2959.67	1.1	0	0.3	0.003	2.19	99.4	0.5	63.3	1.1
Beech	SPI6	3229.89	3229.94	0.6	0.9	0.2	0.001	0.95	99.8	0.1	83.2	0.3
Oak	SPI6	3229.89	3229.94	0.6	0.9	0.2	0.001	0.95	99.6	0.1	51.1	0.2
Baseline	SWS	2959.58	2966.81	137	0.1	0.7	0.244	164.62	53.8	17.1	18.1	46.2
Beech	SWS	3229.89	3235.85	129	0.1	0.7	0.185	130.32	76.2	5.0	35.2	48.3
Oak	SWS	3229.89	3235.85	129	0.1	0.7	0.185	130.50	50.8	20.2	18.4	32.9

B. Optimal insurance contract and effectiveness criteria of the insurance contract (relative risk aversion coefficient of 0.5)

Table IV.B.1: Strike (S), slope-related parameter (λ) and maximum of indemnity (M) of the optimal insurance contract, the percentage of gain of certain equivalent income with insurance (CEI_{ins}, in EUR) compared to the initial one (CEI_o, in EUR), the annual premium (in EUR), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of type I (BR_I) and type II (BR_II) basis risk and the percentage of the number of cases corresponding to real losses compensated (Real_loss) for each index for the baseline (unique contract) and the species-specific contracts (beech and oak) considering an age-biomass class of 40-5000 and a relative risk aversion coefficient of 0.5.

Species	Index	CEI_o	CEI_ins	S	λ	M	Gain	Premium	Comp_loss	BR_I	BR_II	Real_loss
Baseline	CP3	3321.84	3323.92	141.7	0	0.6	0.063	72.82	67.8	11.8	28.6	17.6
Beech	CP3	2826.41	2827.89	231.7	0.1	0.3	0.052	132.88	70.8	17.1	18.2	55.7
Oak	CP3	3797.32	3799.93	131.7	0	0.8	0.069	78.46	43.8	13.9	18.4	10.3
Baseline	CP6	3321.84	3322.81	313.5	0	0.7	0.029	43.36	80.8	9.9	32.7	13.5
Beech	CP6	2826.41	2827.31	473.5	0.1	0.3	0.032	103.02	77.4	17.5	18.5	55.4
Oak	CP6	3797.32	3798.45	293.5	0	0.9	0.030	39.61	71.6	10.5	21.7	6.9
Baseline	SPI3	3321.84	3322.58	3.2	0.1	0.3	0.022	55.17	75.6	18.6	25.6	20.6
Beech	SPI3	2826.41	2826.90	3	0.3	0.2	0.017	39.10	91.4	7.7	48.0	25.9
Oak	SPI3	3797.32	3798.17	3.1	0	0.4	0.022	60.56	56.6	23.5	15.9	12.8
Baseline	SPI6	3321.84	3321.89	0.6	0.9	0.3	0.002	1.42	99.4	0.1	45.9	0.2
Beech	SPI6	2826.41	2826.50	1.2	0.2	0.3	0.003	3.36	99.3	0.5	72.5	1.4
Oak	SPI6	3797.32	3797.36	0.6	0.9	0.2	0.001	0.95	99.3	0.2	28.5	0.2
Baseline	SWS	3321.84	3326.23	133	0	0.9	0.132	187.04	17.3	28.0	12.2	34.0
Beech	SWS	2826.41	2830.51	143	0.1	0.7	0.145	222.52	51.1	16.2	14.4	59.5
Oak	SWS	3797.32	3801.54	127	0.1	0.9	0.111	161.73	115.8	32.4	9.7	19.0

Table IV.B.2: Strike (S), slope-related parameter (λ) and maximum of indemnity (M) of the optimal insurance contract, the percentage of gain of certain equivalent income with insurance (CEI_{ins}, in EUR) compared to the initial one (CEI_0, in EUR), the annual premium (in EUR), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of type I (BR_I) and type II (BR_II) basis risk and the percentage of the number of cases corresponding to real losses compensated (Real_loss) for each index for the baseline (unique contract) and the species-specific contracts (beech and oak) considering an age-biomass class of 70-7000 and a relative risk aversion coefficient of 0.5.

Species	Index	CEI_o	CEI_ins	S	λ	M	Gain	Premium	Comp_loss	BR_I	BR_II	Real_loss
Baseline	CP3	3160.26	3162.08	141.7	0.1	0.5	0.058	67.39	76.1	9.6	34.6	19.7
Beech	CP3	2764.81	2766.13	231.7	0	0.3	0.048	119.63	75.7	14.5	19.4	58.3
Oak	CP3	3538.34	3540.57	131.7	0	0.7	0.063	68.65	63.9	11.1	25.8	13.1
Baseline	CP6	3160.26	3161.12	313.5	0.1	0.6	0.027	41.30	85.4	8.0	39.0	15.4
Beech	CP6	2764.81	2765.63	453.5	0.1	0.3	0.029	90.95	81.5	13.8	23.2	54.5
Oak	CP6	3538.34	3539.32	293.5	0.3	0.6	0.028	37.70	80.2	8.4	29.9	9.1
Baseline	SPI3	3160.26	3160.91	3.1	0.1	0.3	0.020	50.46	82.1	14.0	32.1	22.3
Beech	SPI3	2764.81	2765.26	3	0.2	0.2	0.016	34.40	93.0	6.5	50.7	27.1
Oak	SPI3	3538.34	3539.08	3.2	0.1	0.3	0.021	55.17	71.0	21.2	20.9	18.0
Baseline	SPI6	3160.26	3160.31	0.6	0.9	0.3	0.001	1.42	99.5	0.1	54.1	0.2
Beech	SPI6	2764.81	2764.90	1.3	0.1	0.3	0.003	3.64	99.3	0.5	76.0	1.8
Oak	SPI6	3538.34	3538.37	0.6	0.9	0.2	0.001	0.95	99.5	0.1	38.8	0.2
Baseline	SWS	3160.26	3164.33	135	0.2	0.7	0.129	184.20	34.8	23.0	14.5	39.9
Beech	SWS	2764.81	2768.75	144	0.2	0.6	0.143	206.15	58.2	13.2	16.5	61.3
Oak	SWS	3538.34	3542.06	129	0	0.9	0.105	153.04	19.5	27.6	13.0	26.0

Table IV.B.3: Strike (S), slope-related parameter (λ) and maximum of indemnity (M) of the optimal insurance contract, the percentage of gain of certain equivalent income with insurance (CEI_{ins}, in EUR) compared to the initial one (CEI_0, in EUR), the annual premium (in EUR), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of type I (BR_I) and type II (BR_II) basis risk and the percentage of the number of cases corresponding to real losses compensated (Real_loss) for each index for the baseline (unique contract) and the species-specific contracts (beech and oak) considering an age-biomass class of 100-9000 and a relative risk aversion coefficient of 0.5.

Species	Index	CEI_o	CEI_ins	S	λ	M	Gain	Premium	Comp_loss	BR_I	BR_II	Real_loss
Baseline	CP3	2991.66	2993.21	141.7	0	0.5	0.052	60.68	83.0	7.5	42.4	21.9
Beech	CP3	3283.58	3285.43	131.7	0.2	0.5	0.056	61.10	88.8	2.3	61.6	21.9
Oak	CP3	3283.58	3285.43	131.7	0.2	0.5	0.056	61.10	77.0	8.2	35.3	15.9
Baseline	CP6	2991.66	2992.40	313.5	0	0.6	0.025	37.17	89.6	6.2	47.1	17.2
Beech	CP6	3283.58	3284.40	293.5	0.2	0.6	0.025	33.01	94.0	1.7	67.8	15.7
Oak	CP6	3283.58	3284.40	293.5	0.2	0.6	0.025	33.01	87.5	6.2	40.1	11.2
Baseline	SPI3	2991.66	2992.21	3.1	0	0.3	0.018	45.42	87.3	10.8	38.8	25.5
Beech	SPI3	3283.58	3284.20	3.2	0	0.3	0.019	49.66	90.9	5.9	50.2	33.3
Oak	SPI3	3283.58	3284.20	3.2	0	0.3	0.019	49.66	81.3	16.1	28.3	23.0
Baseline	SPI6	2991.66	2991.70	0.6	0.9	0.2	0.001	0.95	99.7	0.1	64.1	0.2
Beech	SPI6	3283.58	3283.60	0.6	0.9	0.2	0.001	0.95	99.8	0.1	83.2	0.3
Oak	SPI6	3283.58	3283.60	0.6	0.9	0.2	0.001	0.95	99.6	0.1	51.1	0.2
Baseline	SWS	2991.66	2995.37	138	0	0.8	0.124	174.03	51.2	17.7	17.5	46.9
Beech	SWS	3283.58	3286.78	131	0	0.8	0.097	142.66	73.9	5.4	33.1	50.4
Oak	SWS	3283.58	3286.78	131	0	0.8	0.097	142.79	46.1	21.6	17.3	34.0

C. Optimal insurance contract and effectiveness criteria of the insurance contract (relative risk aversion coefficient of 2)

Table IV.C.1: Strike (S), slope-related parameter (λ) and maximum of indemnity (M) of the optimal insurance contract, the percentage of gain of certain equivalent income with insurance (CEI_{ins}, in EUR) compared to the initial one (CEI_o, in EUR), the annual premium (in EUR), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of type I (BR_I) and type II (BR_II) basis risk and the percentage of the number of cases corresponding to real losses compensated (Real_loss) for each index for the baseline (unique contract) and the species-specific contracts (beech and oak) considering an age-biomass class of 40-5000 and a relative risk aversion coefficient of 2.

Species	Index	CEI_o	CEI_ins	S	λ	M	Gain	Premium	Comp_loss	BR_I	BR_II	Real_loss
Baseline	CP3	3189.68	3198.07	161.7	0	0.5	0.263	87.44	61.3	17.2	23.6	22.5
Beech	CP3	2738.15	2743.93	231.7	0	0.3	0.211	119.63	73.7	17.1	18.2	55.7
Oak	CP3	3566.06	3575.14	131.7	0.1	0.6	0.255	65.35	53.2	13.9	18.4	10.3
Baseline	CP6	3189.68	3193.87	323.5	0.2	0.5	0.131	45.23	80.0	11.5	31.2	15.0
Beech	CP6	2738.15	2741.73	473.5	0.1	0.3	0.131	103.02	77.4	17.5	18.5	55.4
Oak	CP6	3566.06	3570.38	303.5	0.2	0.6	0.121	39.35	71.8	12.5	21.0	7.7
Baseline	SPI3	3189.68	3192.46	3.1	0	0.3	0.087	45.42	79.9	17.0	26.9	19.3
Beech	SPI3	2738.15	2740.04	3.1	0.2	0.2	0.069	37.79	91.7	8.5	46.1	27.9
Oak	SPI3	3566.06	3568.31	2.9	0	0.3	0.063	37.43	73.2	19.6	17.3	11.3
Baseline	SPI6	3189.68	3189.92	1.1	0.1	0.3	0.008	2.43	98.9	0.7	45.3	0.9
Beech	SPI6	2738.15	2738.61	1.4	0.1	0.3	0.017	4.35	99.0	0.7	71.9	2.0
Oak	SPI6	3566.06	3566.18	0.6	0.8	0.2	0.003	0.84	99.4	0.2	28.5	0.2
Baseline	SWS	3189.68	3205.77	128	0.3	0.6	0.505	153.45	32.2	23.9	14.5	31.7
Beech	SWS	2738.15	2753.57	143	0	0.7	0.563	200.28	56.0	16.2	14.4	59.5
Oak	SWS	3566.06	3578.47	119	0.2	0.7	0.348	107.58	23.0	24.3	12.0	16.7

Table IV.C.2: Strike (S), slope-related parameter (λ) and maximum of indemnity (M) of the optimal insurance contract, the percentage of gain of certain equivalent income with insurance (CEI_{ins}, in EUR) compared to the initial one (CEI_0, in EUR), the annual premium (in EUR), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of type I (BR_I) and type II (BR_II) basis risk and the percentage of the number of cases corresponding to real losses compensated (Real_loss) for each index for the baseline (unique contract) and the species-specific contracts (beech and oak) considering an age-biomass class of 70-7000 and a relative risk aversion coefficient of 2.

Species	Index	CEI_o	CEI_ins	S	λ	M	Gain	Premium	Comp_loss	BR_I	BR_II	Real_loss
Baseline	CP3	3046.26	3053.62	151.7	0	0.5	0.242	73.59	73.9	11.9	31.6	22.7
Beech	CP3	2683.66	2688.89	231.7	0	0.3	0.195	119.63	75.7	14.5	19.4	58.3
Oak	CP3	3344.45	3352.35	131.7	0	0.6	0.236	58.84	69.0	11.1	25.8	13.1
Baseline	CP6	3046.26	3049.94	333.5	0.1	0.5	0.121	46.49	83.5	10.9	35.6	18.8
Beech	CP6	2683.66	2686.92	483.5	0	0.3	0.121	98.14	80.1	15.5	18.2	59.6
Oak	CP6	3344.45	3348.19	303.5	0	0.7	0.112	36.73	80.7	10.1	28.8	10.1
Baseline	SPI3	3046.26	3048.75	3.1	0	0.3	0.082	45.42	83.9	14.0	32.1	22.3
Beech	SPI3	2683.66	2685.40	3	0.2	0.2	0.065	34.40	93.0	6.5	50.7	27.1
Oak	SPI3	3344.45	3346.54	2.9	0	0.3	0.063	37.43	80.3	16.0	24.0	14.9
Baseline	SPI6	3046.26	3046.48	1.1	0	0.3	0.007	2.19	99.2	0.6	53.4	1.0
Beech	SPI6	2683.66	2684.09	1.4	0	0.3	0.016	3.91	99.2	0.6	75.6	2.1
Oak	SPI6	3344.45	3344.56	0.6	0.8	0.2	0.003	0.84	99.6	0.1	38.8	0.2
Baseline	SWS	3046.26	3061.34	131	0	0.8	0.495	150.03	46.9	20.2	16.8	37.6
Beech	SWS	2683.66	2698.63	143	0	0.7	0.558	188.00	61.8	12.8	17.2	60.6
Oak	SWS	3344.45	3355.79	122	0.1	0.7	0.339	104.91	44.8	21.4	15.9	23.0

Table IV.C.3: Strike (S), slope-related parameter (λ) and maximum of indemnity (M) of the optimal insurance contract, the percentage of gain of certain equivalent income with insurance (CEI_{ins}, in EUR) compared to the initial one (CEI_0, in EUR), the annual premium (in EUR), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of type I (BR_I) and type II (BR_II) basis risk and the percentage of the number of cases corresponding to real losses compensated (Real_loss) for each index for the baseline (unique contract) and the species-specific contracts (beech and oak) considering an age-biomass class of 100-9000 and a relative risk aversion coefficient of 2.

Species	Index	CEI_0	CEI_ins	S	λ	M	Gain	Premium	Comp_loss	BR_I	BR_II	Real_loss
Baseline	CP3	2895.45	2901.73	151.7	0.1	0.4	0.217	65.38	81.7	9.2	38.9	25.4
Beech	CP3	3124.45	3131.11	131.7	0.1	0.5	0.213	54.46	90.0	2.3	61.6	21.9
Oak	CP3	3124.45	3131.11	131.7	0.1	0.5	0.213	54.46	79.5	8.2	35.3	15.9
Baseline	CP6	2895.45	2898.62	333.5	0	0.5	0.109	41.84	88.3	8.5	43.1	21.2
Beech	CP6	3124.45	3127.61	303.5	0.2	0.5	0.101	32.79	94.0	2.1	65.4	18.1
Oak	CP6	3124.45	3127.61	303.5	0.2	0.5	0.101	32.79	87.6	7.6	38.6	12.6
Baseline	SPI3	2895.45	2897.59	3.2	0.2	0.2	0.074	41.32	88.4	11.8	37.0	27.3
Beech	SPI3	3124.45	3126.33	3	0.2	0.2	0.060	34.40	93.7	4.7	54.7	28.8
Oak	SPI3	3124.45	3126.33	3	0.2	0.2	0.060	34.40	87.0	13.5	31.2	20.1
Baseline	SPI6	2895.45	2895.64	1.1	0	0.3	0.007	2.19	99.4	0.5	63.3	1.1
Beech	SPI6	3124.45	3124.54	0.6	0.8	0.2	0.003	0.84	99.8	0.1	83.2	0.3
Oak	SPI6	3124.45	3124.54	0.6	0.8	0.2	0.003	0.84	99.7	0.1	51.1	0.2
Baseline	SWS	2895.45	2909.33	134	0.2	0.6	0.479	145.76	59.1	15.5	20.2	44.1
Beech	SWS	3124.45	3134.55	125	0	0.7	0.323	102.91	81.2	4.1	39.5	44.0
Oak	SWS	3124.45	3134.55	125	0	0.7	0.323	103.15	61.1	17.4	20.8	30.4

Conclusion

This thesis aimed at (i) testing and comparing different management-based adaptation options as a way to mitigate drought-induced risk of forest dieback, both in terms of financial balance supported by the forest owner and in terms of carbon balance supported by the society, and (ii) proposing a new market-based adaptation option in the form of an index-based insurance contract covering drought-induced risk.

Summary of the main results

The main results of this thesis, for the considered case studies and under some assumptions, can be summarized as follows. First, the results proved that adaptation is a relevant strategy to mitigate drought-induced risk of dieback. From an economic perspective, the implementation of either management-based adaptation or market-based adaptation is always preferable to adopting a "do-nothing" scenario. In other words, the benefits associated with new forest management practices always outweigh the costs of their implementation; or the utility with insurance always outweigh the utility without insurance. Second, combining different management-based adaptation strategies appeared as a relevant way to adapt forests in a context of an increasing drought-induced risk of forest dieback. Indeed, the combination of different strategies was found to be more beneficial for the forest owner than each strategy implemented separately (synergy *vs*. additionality) (Chapters I to III). However, not all adaptation options appeared effective. Maladaptation arises when, under certain conditions, adaptation efforts increase the vulnerability of trees and/or adaptation costs outweigh (Chapters I to III). Finally, while forest insurance contracts covering drought-induced risk of forest dieback could be a market-based option, small gains associated with current contracts are likely to prevent forest owners from adopting such insurance products (Chapter IV).

Conceptual contributions

First, this thesis explores a wide range of adaptation strategies. Indeed, four types of adaptation strategies were tested and compared. These are: incremental (Chapter I), transitional (Chapters II and III) and transformational (Chapter I) management-based adaptation as well as a market-based adaptation (Chapter IV). The results of this thesis results demonstrated that there is not a single adaptation strategy to drought-induced risk of forest dieback but rather a range of strategies. We also showed that, from an economic standpoint, all adaptation options were effective and can be combined.

Second, this thesis constitutes the first attempt at studying a combination of management-based adaptation strategies. The combination of strategies can offer flexibility to forest owners in addition to mitigating damages associated with climate change. For example, combining composition diversification with the reduction of rotation lengths increase the flexibility of forest management by offering a wider range of solutions and reducing the time horizon of the decision respectively. In addition to this, the results of this thesis showed synergies between adaptation strategies, thus indicating that forest owners could reap higher benefits by implementing adaptation strategies jointly rather than separately.

Third, a new model of forest insurance was proposed for a new type of risk, severe drought. Indeed, while the risk of storm and/or fire is often covered under traditional insurance contracts, insurers do not currently offer contracts covering the risk of severe drought. An *ex ante* index-based insurance option that aims at compensating forest owners for drought-induced risk of forest dieback was developed (Chapter IV). Such an insurance contract can offer potential levers to public authorities to encourage forest owners to adapt to climate change.

Fourth, this thesis explored the combined impact of two independent risks, drought- and windstorm-induced, from an economic standpoint. To the best of our knowledge, this is the first study to investigate those two risks together. The results of this study provide evidence that analysing windstorm and drought risks simultaneously affects the conclusions and recommendations compared to investigating each risk separately. On the one hand, a strategy could be relevant to cope with both risks, whether separately or simultaneously. On the other hand, a strategy could be suitable to cope with either a single risk or only both risks simultaneously. This preliminary study suggests that further research is needed on this topic. Additional multi-risks analysis should be conducted to provide forest owners with a variety of adaptation strategies suitable to different climate change-related risks, instead of risk-specific adaptation strategies.

Methodological contributions

First, the methodology of this thesis was based on forest-growth models (*i.e.*, CASTANEA and MATHILDE) coupled with commonly-used economic tools (*i.e.*, land expectation value criterion and insurance model). These models and tools has been adapted to the research objectives. CASTANEA was developed for management purposes and to compute Douglas-fir productivity. MATHILDE was developed to compute the growth of uneven-aged stands and different proportions of species mixtures and future climate scenarios.

Second, the forest economic approaches proposed by Faustmann, Hartman, and Reed were combined and adjusted. Faustmann's model was developed for monospecific and even-aged stands and considered both the stand value and the soil value from a deterministic perspective (Faustmann, 1849). Hartman (1976) and Reed (1984) developed Faustmann's model to take into account amenities in addition to timber objectives and exogenous risk respectively. This thesis takes all of the above-mentioned variables into consideration and complements earlier studies by exploring (i) one specific amenity (*i.e.*, carbon sequestration), (ii) two endogenous risks (*i.e.*, drought-induced risk of forest dieback separately, and in combination with windstorm-induced risk), and (iii) a stochastic approach through the development of the double-weighted land expectation value.

Third, the combination of ecological and economic tools enabled the comparison and inclusion of two ecosystem services - carbon sequestration capacity and timber production - in this analysis. Carbon sequestration capacity represented here the sum of aboveground carbon, belowground carbon (Chapters I to III), often neglected in studies, and carbon stored in wood products (Chapters II and III). Moreover, the approach for measuring carbon sequestration considered three accounting methods. These are: market value, shadow price, and social cost of carbon (Chapters II and III). The results of this thesis demonstrated that, in the context of rapid climate change, carbon sequestration should be added to timber production when computing forest owners' profitability measures. The addition of carbon services increased forest stand value (LEV) (Chapters I to III). Moreover, the results showed the importance of clearly defining the carbon accounting method in relation to specific objectives. Indeed, the three carbon prices used provided different economic returns and therefore could influence the recommendations in terms of adaptation strategies, *i.e.,* introducing carbon services in the analysis can influence the scenario identified as the best strategy (Chapters II and III). Bringing the fields of forest ecology and forest economics together led to the emergence of more effective and balanced solutions in terms of achieving both timber objectives and carbon objectives (Chapter I). However, it also revealed the potential conflicts and/or trade-offs between the two objectives (Chapters I to III). Indeed, ecologically efficient adaptation strategies were not always the most economically beneficial options, and *vice versa*.

Fourth, previous published studies conducted from an economic viewpoint rarely considered the impact of climate change (see Hanewinkel *et al.* (2010) as an exception). In this thesis, climate change was taken into consideration by examining two extremes climate scenarios (*i.e.*, RCP 4.5 and RCP 8.5). Additionally, future drought and windstorm recurrences were estimated for the region under study (Chapters II and III).

Fifth, optimal index-based insurance contracts were examined using multiple indices of increasing complexity. The analysis of these different indices showed that the best insurance contract was not correlated with the complexity of the index.

Public policies issues

The above-described conceptual and methodological contributions may serve as a basis for designing and implementing public policies. Indeed, the French government has made several commitments to mitigate climate change, such as the Paris Agreement and attaining carbon neutrality by 2050. In a context of international negotiations surrounding the achievement of these climate goals, public authorities are expected to adopt forest adaptation strategies. In France, three-quarters of the metropolitan forested area is privately owned (IGN[18], 2019). As such, the successful adaptation of the French forests greatly depends on management decisions made by 3.5 million private forest owners. However, forest owners do not sufficiently use management-based adaptations (Andersson and Keskitalo, 2018) nor market-based adaptations to cope with climate change (Dossier Sylvassur, 2013). While forest owners are aware of climate change, they lack reliable information regarding forest adaptation strategies; thus delaying the implementation of such strategies (Yousefpour and Hanewinkel, 2015; Sousa-Silva *et al.*, 2016). Additionally, forest owners are reluctant to experiment adaptation strategies due to the large degree of uncertainty that still exists concerning the effectiveness of such management methods. This thesis offers some guidance to forest owners interested in adapting their forest stands as well as potential levers for public authorities to encourage them to adapt.

As demonstrated by Sousa-Silva *et al.* (2018), policy and financial incentives may be required in order to make forest owners and managers more likely to undertake adaptation actions. Indeed, subsidy programs created by public authorities can encourage forest owners to choose

[18] French National Forest Inventory.

adaptation, assisting them in the implementation of either management-based options or market-based options.
In light of new management options, the forest sector will need to adjust quickly to silvicultural changes. It is likely that governments will also have a role to play. As amenities provide the opportunity to earn credits, forest owners could receive payment for the ecosystem services provided by their stands (Dwivedi *et al.*, 2012). This payment can be seen as an incentive to implement alternative forest management that can provide different ecosystem services in addition to the current one(s).
Additionally, a combination of adaptation strategies should be encouraged as a way to improve the effectiveness of the adaptation process. Through financial support, public authorities could motivate forest owners to develop a portfolio of proven strategies. This thesis demonstrated that an adaptation strategy could be effective for different types of risks (Chapter III) and climate objectives (adaptation to climate-related risk(s) and mitigation to climate change) (Chapter I).
Insurance contracts can also serve as a risk management tool. They can provide forest owners with an incentive to implement new forest management practices (Brunette *et al.*, 2017) as well as potential levers for public authorities. More specifically, French public authorities could subsidize insurance premiums, as it is already the case in other countries (*e.g.*, Germany for forest fire). The literature provides some insights on the impact of subsidization on forest owners' demand for insurance contracts. It has been suggested that an *ex ante* public transfer to the insurer (Loisel *et al.*, 2020) or to the insured (Sauter *et al.*, 2016) might result in reduced insurance premiums, and consequently increase consumers' demand for insurance products. As suggested by several studies (Subak, 2003; Figueiredo *et al.*, 2005) carbon can be included into timber insurance contracts. Likewise, several risks can be covered by the same contract. Since drought insurance contracts (including index-based contracts) already exists in the agricultural sector, a joint insurance between forest and agriculture could be developed. Such contracts would insure the same types of risk but for different types of land while taking into account different time-scale of production and exposure to risk.

Additionally, French forests suffer from a high degree of fragmentation (12.5 million hectares shared by 3.5 million of private owners), which can slow down the adaptation process. As recommended by the French forest and timber program (PNFB, 2016-2026), public authorities could improve the implementation of new and adapted measures by encouraging the regrouping of forest stands; a process that could also lead to shared forest investments. For example, when it comes to adaptation, public financial aid can only be granted if the stand exceeds a certain surface area. The large-scale adoption of adaption strategies requires that administrative locks be removed. Examples include: considering mixed stands as monospecific, simplifying owners' access to administrative files, streamlining administrative processes in order to disburse financial help promptly after a disaster, or help forest owners' grouping. Moreover, making adaptation options available is a first step. Further investigations are needed to better understand how these options can be implemented successfully (*e.g.*, need for technical assistance; Sousa-Silva *et al.*, 2018). Financial aid can support arboretums (*e.g.*, testing new species and provenances) and experimental stands (*e.g.*, testing new management practices), which can certainly help researchers in this endeavour.

Future research

This thesis investigated adaptation to drought-induced risk of forest dieback through two case studies (Bourgogne and Grand-Est regions) and three species. These are: beech (main species), oak (species that can be added to beech stands), and Douglas-fir (species that can be used as a substitute to beech). Adaptation to drought-induced risk of forest dieback was investigated by testing the following adaptation strategies: reduction of rotation length, initial stand density reduction, diversification of stand composition, diversification of stand structure, species substitution, and index-based insurance contracts. The combined risks of drought and windstorm on forest productivity was also investigated. Two forest-growth models were used (CASTANEA, and MATHILDE) along with two distinct economic tools (LEV, insurance model). The findings of this thesis are based on specific assumptions and are only applicable to the context of this study. They cannot be generalized to other case studies (*i.e.*, other site conditions, species, climate scenarios, adaptation strategies, or natural hazards). However, the methodological approach adopted throughout this work (*i.e.*, bridging ecological and economic considerations) can be replicated in order to expand the body of knowledge on similar research topics.

Methodological aspects. This thesis showed that, under some assumptions and for the considered case studies, adaptation is needed and relevant for coping with drought-induced risk of forest dieback. However, the four different types of adaptation strategies have not been tested and compared in the same analysis. The synergy between two types of adaptation provided a robust result (Chapter I). It can be interesting to test other combinations of options (*e.g.,* reduced density with species mixture) with different species, site conditions, water availability, *etc.* Indeed, uncertainty on future climate induces uncertainty on the evolution of site conditions, adaptation of species, and thus on the outcomes of adaptation. Therefore, a single model including a large number of parameters is needed. CASTANEA is specialised on ecophysiological processes, and thus, is particularly well suited for the computation of forest growth in relation to water stress. However, the model was not designed to simulate mixed and uneven-aged stands. MATHILDE, on the contrary, allows for the computation of silvicultural processes using two commonly used criteria in forest management, *i.e.*, basal area and dominant tree diameter. However, the computation of drought processes still requires some improvement.

This thesis employs an innovative approach, which consists of combining forest-growth models with economic tools. A large number of input data were required to run the models. This was made possible through a close collaboration with colleagues from other research disciplines as well as other sectors (*e.g.,* forest managers). While the results are specific to the two case studies under consideration, the methodology can be generalized to other case studies. This thesis explored multiple adaptation strategies on a relatively small scale as well as a single adaptation strategy on a larger scale. Chapters I to III investigate different adaptation strategies at the regional scale for a specific case study, while the fourth chapter focuses on one adaptation strategy at a larger spatial scale (France). Following a similar approach, other case studies can be considered to investigate all of the different types of adaptation strategies on a same analysis, and, ideally at the national level. However, broader studies would require additional input data, and thus depend on both the existence and the availability of data as well as a broad network of stakeholders.

Ecological aspects. This thesis focused on two ecosystem services, namely, timber production and carbon sequestration. Further research could be conducted to analyse and include other ecosystem services. While certain adaptation strategies can be beneficial to a variety of ecosystem services (*e.g.,* diversification strategy for wood productivity, biodiversity, and protection against soil erosion), others can introduce conflicts (*e.g.,* species substitution can reduce recreation and biodiversity). Within the context of drought-induced risk of forest dieback adaptation, the integration of other ecosystem services, such as partitioning between blue and green water[19], should offer additional insights to this work. Indeed, hydrology-based silviculture can increase water availability at the stand scale by increasing green/blue water ratio.

The addition of climate change scenarios brought some heterogeneity to the results of this thesis. This may be due to the fact that the models used are based on stationary time series/analysis. Testing the results with a dynamic model can be a worthwhile approach as more precise information about climate change realisation and impacts become available over time. This can be done through (quasi-) option value (Arrow and Fischer, 1974; Henry, 1974); a method that allows for flexibility in decision-making (Brunette *et al.,* 2014), which was not the case in this study (fixed in time). Another idea can be to consider real option (McDonald and Siegel, 1986). This method can compute optimal decisions for given stochastic processes or lost value from irreversible decisions and investments (Insley, 2002; Jacobsen and Thorsen, 2003). Such approaches should enable forest owners to adjust their decisions to newly available information. These future studies can be more effective if further investigations are performed in conjunction with climate services[20], in order to reduce climate change uncertainty.

In the context of climate change, additional multi-risk analysis may be worth conducting. The results showed that conclusions and recommendations depend on whether risks are examined jointly rather than separately (Chapter III). Consequently, inadequate decisions could be made by studying the impact of a single risk (*i.e.*, ignoring other risks) or only considering the additive effects of independent risks (*i.e.*, ignoring multiplicative effects). The results of this thesis showed the multiplicative effects of drought- and windstorm-induced risks in terms of tree mortality. Considering a single risk can underestimate the intensity of impacts. Further studies are also needed to test if adaptation options are suitable for major types of risk. For example, diversification can be a suitable strategy to cope with drought- and windstorm-induced risks, and may help forest owners fight against insect pests as well (Griess and Knoke, 2011; Jactel *et al.*, 2017). Reversely, shifting to a more drought-tolerant species (*e.g.,* maritime pine) can weaken the stands' ability to withstand storm-force winds. Moreover, invisible damage caused by drought in the short run can result in severe dieback later. This complex effect can come from a set of secondary risks (*e.g.,* insects, pathogens, fire) that are linked to drought and can be more damageable than drought (Desprez-Loustau *et al.,* 2006; Rouault *et al.,* 2006; Stephens *et al.*, 2018). This thesis investigated two independent risks, namely, drought and windstorm. Future

[19] Blue water refers to the amount of rainfall that enters lakes, rivers, and groundwater. Green water corresponds to the amount of rainfall that either is intercepted by the vegetation or enters the soil, taken up by plants, and evapotranspired back into the atmosphere.

[20] Climate services are all the information and services that make it possible to evaluate and qualify the past, present or future climate, to assess the impacts of climate change on economic activity, society and the environment, and to provide elements for undertaking mitigation and adaptation measures (French Research Alliance for the Environment, Allenvi).

studies can include investigating the link between dependent risks as well as how this link can be included in models and in terms of adaptation strategies.

Additionally, studies should further investigate trade-offs between adaptation and mitigation. The results of this thesis showed that risk adaptation can have either positive or negative effects on climate change mitigation, and reciprocally (Chapters I to III). Negative effects imply that trade-offs are needed to implement both adaptation and mitigation simultaneously. Consensual solutions can exist between harvesting earlier to reduce the risk exposure *vs*. losing some benefits (if the harvest is too early) and maintaining forests in order to store more carbon *vs*. losing the whole stand and carbon stored in case of damage (if the harvest is too late). The question is not on quantities of carbon stored or the total carbon stock, but rather, on the avoided carbon emissions in the atmosphere or to what extent adaptation can contribute to mitigation. This is the reason why this thesis focused on the carbon balance and not the carbon stock. Future research can further investigate this issue by integrating adaptation with mitigation measures, such as following climate-smart forestry recommendations (Nabuurs *et al.,* 2017; Astrup *et al.*, 2018) and the recommendations by the French forest and timber program (PNFB, 2016-2026).

Economic aspects. Carbon prices as well as timber prices were assumed fixed across time. However, uncertain future climate can induce fluctuations in both prices. The effect of price fluctuations on the financial balance of forest owners can be investigated using past data and/or theoretical trends based on a stochastic evolution of prices (Chladná, 2007). In addition to this, many debates exist about carbon accounting methods. While three methods were tested in this study, another approach could be to take into consideration the future use of wood products. Wood products may have different lifetimes, as well as the carbon stored in these products. This suggests that wood quality and direct wood uses need to be integrated into the analysis. For example, firewood, when burned, directly re-emits sequestered carbon, whereas carbon sequestrated in a wooden table has a longer lifetime (*i.e.*, it takes a longer time span for it to be naturally re-emitted). This approach would make it possible to consider simultaneously (i) the individual negative effect of forest owners' wood production, (ii) the economic consequences of these individual decisions for society, and (iii) the social contribution through different wood products. Indeed, adaptation of timber production by forest owners can have economic consequences in downstream parts of the wood chain through different wood products as well as in downstream landscapes (*e.g.,* the impact on runoff and water pollution in downstream of a mountainous area). In other words, microeconomic decisions (*i.e.*, decisions at the stand level) have macroeconomic impacts (*i.e.*, at the landscape level and the entire forest sector). Forest management consists of managing ecosystems with varied ecological functions while keeping economic constraints and demand into account. Ecological tools are used to identify management practices that are well suited for adaptation, through the simulation of complex tree functions and their interaction with the environment. Economic tools are designed to assess wood quality and consumers' demand for different types of wood/wood products. Building ecological tools with economic ones was required and needs further development. This thesis presents a microeconomic view of forest stand adaptation (upstream) and carbon sequestration. However, forest adaptation implies new supply of timber (*e.g.,* volume, species, quality). To be effective and sustainable, adaptation needs to be connected to the entire forest sector, which can also contribute to climate change mitigation (*e.g.,* carbon sequestration in wood products and substitution of fossil fuels by wood products). Indeed, the French forest and timber program (PNFB, 2016-2026) aims to maximize substitution effects and carbon storage in wood products by influencing supply and demand. The study of these macroeconomic aspects could be undertaken as a complement to this work. Similar to this work, most studies dealing with climate change mitigation usually focus on carbon sequestration. Mitigation of temperature raise by the forest microclimate effect or the albedo effect may have a greater impact than carbon sequestration (Lutz and Howarth, 2014). In addition to this, carbon dioxide (CO_2) is not the only greenhouse gas of interest when dealing with global warming. Methane (CH_4), nitrous oxide (N_2O), water vapour (H_2O), and ozone (O_3), are also considered primary greenhouse gases that can impact forest and mitigation to climate change[21].

Finally, adaptation to drought-induced risk of forest dieback is an important issue and requires further investigations. As forests need adaptation to decreasing water availability ("adaptation for forests", Locatelli *et al.*, 2010), forests are needed for adaptation, *i.e.,* forests reverse desertification trends, protect water resources, and provide other ecosystem services ("forests for adaptation", Locatelli *et al.*, 2010). Indeed, while some might argue that "more trees imply less water", and "not water implies no forest", others may support that "not forest implies no water" (water security *vs*. forest cover). With regard to identifying the best strategy to cope with drought-induced risk, this thesis showed the importance of bridging different fields (ecology and economics) and considering the multiple functions played by forests (timber production and carbon sequestration in this case). This thesis also demonstrated that information about the implementation of silvicultural strategies, collaboration across multiple sectors (forest managers, researchers, and the entire forest sector), as well as further multi-criteria and multi-risks analysis are required. To date, climate studies conducted in the field of forest research have focused on technical aspects and neglected the discipline of social sciences (Andersson and Keskitalo, 2018). Fouqueray and Frascaria-Lacoste (2020) demonstrated that mitigation and adaptation to climate change studies underuse social sciences in forest research. Social sciences can complement (not replace) experimental sciences in climate studies (Fouqueray and Frascaria-Lacoste, 2020). Therefore, future research should be conducted with the goal of expanding and strengthening this connection.

[21] Carbon dioxide, methane and nitrous oxide are among the greenhouses gases covered by Kyoto Protocol that must be mitigated, contrary to water vapour and ozone.

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French summary of the thesis

Analyse économique des stratégies d'adaptation face au risque de dépérissement induit par la sécheresse en forêt : bilan financier et/ou bilan carbone

Contexte et motivation

Les forêts sont des écosystèmes qui jouent un rôle important dans l'adaptation de la société au changement climatique. Elles fournissent des services écosystémiques qui contribuent au bien-être humain (services d'approvisionnement, de régulation, de soutien et culturels) et réduisent la vulnérabilité sociale. Jusqu'à présent, les forêts se sont adaptées pour faire face à diverses perturbations provenant de l'environnement direct (*i.e.*, perturbations abiotiques) et/ou de l'interaction avec d'autres êtres vivants (*i.e.*, perturbations biotiques). Or, le rythme du changement climatique s'accélère, de sorte que les processus naturels et spontanés d'adaptation des forêts ne puissent plus compenser les nombreux impacts négatifs des changements induits par le climat. En effet, le changement climatique provoque l'augmentation de la fréquence, de la durée et de l'intensité des événements naturels, notamment des épisodes de sécheresse extrême.

D'un point de vue écophysiologique, la sécheresse est une réduction de la disponibilité en eau dans le sol suffisamment grave pour empêcher le fonctionnement normal des arbres. Cette diminution est une résultante de précipitations insuffisantes, de températures élevées induisant une évapotranspiration importante, et/ou d'une forte absorption d'eau par les arbres eux-mêmes. La sécheresse est un phénomène naturel qui affecte la productivité et la santé des forêts, notamment lorsque son intensité est extrême. En Europe, les arbres souffrent de graves pénuries d'eau qui se produisent généralement au début de l'été. Bien que la sécheresse soit considérée comme l'un des risques abiotiques les plus dommageables, ses impacts induits sur la santé des forêts ont été sous-estimés pendant très longtemps en raison de dommages invisibles à première vue. Les pénuries d'eau entraînent divers effets à court et moyen/long terme, qui peuvent être plus ou moins graves (et visibles) selon les espèces. Ces effets se matérialisent sous la forme de régulations au niveau des arbres ou de dommages permanents pouvant avoir un impact à l'échelle du peuplement et, en fin de compte, sur des écosystèmes entiers. En effet, au niveau des peuplements, la perte de croissance, qui est proportionnelle à l'intensité de la sécheresse, induit une perte de productivité. Au niveau de l'écosystème, le manque d'eau réduit la plupart des cycles biologiques et affecte les fonctions de la forêt. Cette altération de services fournis par la forêt génère des pertes économiques pour les propriétaires forestiers, ainsi qu'une perte de bien-être et d'aménités pour la société dans son ensemble. En France, les épisodes de sécheresse extrême de 1976 et 2003 ont causé d'importants dommages à la forêt, à la fois immédiatement mais aussi durant plusieurs années. La sécheresse de 2003 a causé plus de dommages qu'en 1976, et celle de 2018 s'est révélée bien plus forte qu'en 2003 tout en touchant une plus grande partie de l'Europe. La ressource hydrique est un facteur clé pour la productivité et la santé des forêts. La fréquence, la durée et l'intensité de la pénurie d'eau représentent ainsi les principales sources de stress pour les forêts.

Dans ce contexte de risque croissant, les forêts doivent s'adapter afin de réduire leur vulnérabilité au risque de dépérissement induit par la sécheresse. En France, les trois quarts des forêts métropolitaines sont privées. Par conséquent, l'adaptation des forêts françaises repose fortement sur les propriétaires privés. Bien qu'ils soient conscients du changement climatique et de ses impacts, seule une minorité d'entre eux adapte leurs forêts de manière proactive. Dans un avenir proche, l'augmentation des dommages induite par le changement climatique, associée à des pertes financières potentiellement plus importantes, est susceptible soit de décourager les investissements forestiers, soit de favoriser l'abandon des forêts (ce qui, à son tour, entraînera une perte des services fournis par les forêts), soit, au contraire, de stimuler la mise en œuvre de stratégies d'adaptation en réponse à la crise forestière.

Les propriétaires privés peuvent protéger leurs forêts grâce à de multiples stratégies d'adaptation. Ces stratégies de gestion des risques peuvent être classées en deux catégories : les adaptations basées sur la gestion forestière (*management-based adaptation*) et les adaptations basées sur les mécanismes de marché (*market-based adaptation*). La première catégorie peut être sous-divisée en trois types d'adaptations : progressive, transitoire et transformante. Plus précisément, différentes stratégies d'adaptation basées sur la gestion forestière sont recommandées afin d'améliorer l'efficacité de la consommation d'eau du peuplement forestier et donc sa résistance au risque sécheresse. Premièrement, les stratégies d'adaptation progressives, telles que la réduction de la révolution et la réduction de la densité du peuplement, peuvent permettre de réduire respectivement le temps d'exposition aux épisodes de sécheresse et la demande en eau. Deuxièmement, l'augmentation de la diversité des peuplements peut favoriser le développement de peuplements forestiers plus stables et capables de se protéger des fluctuations et perturbations climatiques. Cette stratégie d'adaptation transitoire peut être mise en œuvre en mélangeant les espèces actuelles du peuplement avec une ou plusieurs espèces introduites, afin de favoriser la complémentarité entre arbres. Toutefois, un mélange inapproprié peut également avoir certains effets néfastes tels qu'une augmentation de la concurrence pour les ressources en eau. Une autre possibilité est de conserver les espèces actuelles tout en modifiant la structure du peuplement *via* le mélange de différentes classes de diamètre (ou d'âge). Cette stratégie est associée à une plus grande résistance au vent et à une plus grande résilience aux risques naturels. Troisièmement, la mise en place d'une adaptation transformante peut se traduire par le remplacement de l'espèce actuelle par une autre plus adaptée, potentiellement plus tolérante à la sécheresse et/ou plus productive. En effet, il est probable que certaines zones géographiques deviennent favorables à l'installation d'espèces absentes initialement et/ou inadaptées aux espèces historiquement présentes. Concernant les adaptations basées sur les mécanismes de marché, l'assurance est une stratégie, qui permet de partager et donc de redistribuer les risques. Le principe consiste à transférer le risque de l'assuré à l'assureur : le propriétaire forestier reçoit une indemnité en cas de catastrophe, en échange du paiement d'une prime d'assurance annuelle. Dans la plupart des pays européens, des contrats d'assurance forestière sont disponibles pour les risques tempête et/ou incendie. Des recommandations sont également faites par des instances et accords internationaux (OCDE, CCNUCC, Conseil de l'agenda mondial sur le changement climatique, protocole de Kyoto) de façon à promouvoir l'utilisation de l'assurance comme un moyen de financer la résilience et l'adaptation au climat.

Les forêts jouent également un rôle majeur dans l'atténuation du changement climatique grâce à la séquestration du carbone par photosynthèse. Faire face aux risques liés au changement climatique peut simultanément atténuer le changement climatique en maintenant ou en augmentant ces stocks de carbone. En outre, une inquiétude grandissante apparait concernant le maintien de cette capacité d'atténuation, alors que la disponibilité en eau diminue et que le risque sécheresse augmente. Des sécheresses plus longues et des températures plus élevées peuvent avoir un impact négatif sur le rôle de puits de carbone des forêts et même transformer les forêts en source de carbone (par exemple, les forêts tropicales). Par conséquent, l'atténuation du changement climatique peut s'avérer impossible sans adaptation. Enfin, dans un contexte où le secteur forestier est considéré comme un levier essentiel dans les accords internationaux pour atteindre les objectifs climatiques, le gouvernement français a pris plusieurs engagements, dont l'Accord de Paris et l'atteinte de la neutralité carbone d'ici 2050.

Cette thèse a donc pour objectif de (i) tester et comparer différentes options d'adaptation basées sur la gestion forestière, visant à réduire la sécheresse dans les forêts afin d'éviter le risque projeté de dépérissement, à la fois en termes d'équilibre financier pour le propriétaire forestier et de bilan carbone pour la société, et de (ii) proposer une nouvelle option d'adaptation basée sur les mécanismes de marché sous la forme d'un contrat d'assurance contre le risque de dépérissement induit par la sécheresse.

Description des chapitres

La thèse se compose de quatre chapitres. L'objectif des trois premiers chapitres est de tester et de comparer différentes stratégies en termes de gestion forestière en tant que moyens d'adaptation potentiels pour réduire le risque de dépérissement induit par la sécheresse d'un point de vue économique. Les coûts et bénéfices économiques de ces stratégies d'adaptation sont analysés du point de vue du propriétaire forestier privé (bilan financier), tout en considérant l'impact de ces décisions stratégiques sur le stockage du carbone (bilan carbone). L'analyse est basée sur deux études de cas du hêtre en France. En effet, le hêtre est l'une des espèces les plus répandues en France, et des épisodes de sécheresse répétés devraient entraîner une baisse de sa productivité dans un avenir proche. En termes de méthodes, des modèles de croissance forestière ont été combinés avec une approche économique. Les données de sortie des modèles de croissance ont servi de données d'entrée à l'approche économique. Les modèles utilisés ont permis de simuler la croissance des forêts, ainsi que le bilan du carbone aérien et souterrain. Ce dernier, qui représente plus de la moitié du stock de carbone de la forêt, est bien souvent négligé dans les études. Afin de tenir compte de l'incertitude liée au changement climatique, deux scénarios du GIEC ont été utilisés, le RCP 4.5 étant le plus optimiste et le RCP 8.5 le plus pessimiste. Les pertes dues au risque de dépérissement induit par la sécheresse ont été examinées d'un point de vue strictement financier, ainsi qu'en termes de séquestration du carbone. Différentes stratégies d'adaptation ont été comparées et combinées. Les trois chapitres se distinguent par les stratégies d'adaptation testées, les modèles de croissance forestière utilisés, l'évaluation économique réalisée et la manière dont la valeur économique de la séquestration du carbone a été prise en compte.

Le **premier chapitre** se concentre sur l'étude de cas du hêtre en région Bourgogne. La Bourgogne est une région française fortement boisée, où les forêts de feuillus ont souffert de nombreux dépérissements au cours des dernières années. Lors du renouvellement des peuplements, les propriétaires forestiers ont progressivement remplacé les espèces indigènes par des espèces plus productives et plus valorisées, telles que le douglas, et ont adopté une sylviculture plus dynamique afin de compenser les dommages futurs liés au changement climatique, d'éviter les pertes financières et de répondre à une demande croissante de bois. Toutefois, d'autres stratégies d'adaptation existent et peuvent être envisagées. Pour cela, deux stratégies d'adaptation progressives, la réduction de la révolution et la réduction de la densité initiale du peuplement, ont été testées avec la substitution du hêtre par le douglas (adaptation transformante). Deux niveaux de risque sécheresse ont été considérés, basés sur deux niveaux de capacité hydrique du sol : intermédiaire et faible. Un modèle de croissance forestière, CASTANEA, a été combiné avec une approche traditionnelle d'économie forestière se basant sur le critère du Bénéfice Actualisé en Séquence Infinie (BASI). CASTANEA est un modèle mécaniste permettant de simuler le fonctionnement des principales essences d'arbres européennes gérées. Le modèle simule les principaux stocks de l'écosystème forestier (*i.e.*, le carbone, l'eau et l'azote) à la fois aérien et souterrain. Il intègre le risque de mortalité lié au stress hydrique et prend en compte la spécificité de chaque espèce. Les données de sortie de CASTANEA (*i.e.*, la production de bois et la séquestration du carbone) ont été utilisées pour fournir une comparaison économique des stratégies d'adaptation étudiées. L'analyse économique a été réalisée en utilisant à la fois le modèle de Faustmann et le modèle de Hartman. Le BASI de Faustmann prend en compte les coûts et les bénéfices liés à la production de bois, tandis que le BASI de Hartman prend également en compte les bénéfices liés aux aménités, dans notre cas la séquestration du carbone. Les bénéfices de la séquestration du carbone ont été calculés en utilisant le coût social du carbone. La maximisation des BASI a montré que l'adaptation offrait la meilleure rentabilité économique, par opposition au scénario de base ou au scénario "ne rien faire". La combinaison de stratégies s'est révélée être un moyen pertinent pour adapter les forêts face au risque de dépérissement des forêts induit par la sécheresse. En effet, la substitution du hêtre par le douglas, combinée à une réduction de la densité initiale et de la révolution (*i.e.*, la combinaison des trois stratégies d'adaptation considérées), était la meilleure stratégie, quel que soit le niveau de risque sécheresse et le scénario climatique considérés. D'un point de vue économique, la combinaison de différentes stratégies était donc plus bénéfique pour le propriétaire forestier que de considérer chaque stratégie séparément (synergie *vs*. additionnalité). Enfin, les scénarios bénéfiques d'un point de vue écologique n'étaient pas nécessairement bénéfiques en termes économiques et *vice versa*. Dans ce chapitre, le modèle CASTANEA a été utilisé pour la première fois à des fins de gestion forestière. Cependant, bien qu'étant adaptée à la question de recherche traitée, l'architecture du modèle CASTANEA ne permettait pas de simuler des mélanges de peuplements intraspécifiques (futaies irrégulières) et interspécifiques (mélange d'espèces).

Dans le **deuxième chapitre**, MATHILDE, un modèle basé sur l'arbre, a été utilisé pour étudier la diversification, une adaptation transitoire, comme stratégie d'adaptation potentielle au risque de dépérissement des forêts induit par la sécheresse. Le deuxième chapitre se concentre sur l'étude de cas du hêtre en région Grand-Est, une autre région française fortement boisée. Le hêtre et le chêne sont des espèces souvent co-occurrentes, et les forêts mixtes de ces deux essences sont courantes en Europe. En outre, le chêne est plus tolérant à la sécheresse que le hêtre et peut accroître la résistance à la sécheresse et la résilience du hêtre grâce à une facilitation interspécifique. Deux types de diversification ont été testés : le mélange du hêtre avec le chêne (dans différentes proportions de mélange) et le mélange de différentes classes de diamètre d'arbre (*i.e.*, futaie irrégulière), ce dernier n'ayant jamais été analysé comme une stratégie d'adaptation potentielle. MATHILDE a été combinée avec une approche traditionnelle d'économie forestière utilisant le critère du BASI. MATHILDE est un modèle permettant de simuler les peuplements réguliers et irréguliers gérés, ainsi que les peuplements purs et mixtes de hêtres et de chênes sessiles dans le nord de la France. Le modèle a été développé au sein de la plateforme CAPSIS, qui contient un outil de comptabilisation du carbone (CAT). CAT permet de représenter les cycles de vie complexes des émissions inhérents aux forêts gérées. Des simulations ont été réalisées sous différentes récurrences de sécheresse, conséquences du changement climatique. Les données de sortie de MATHILDE (production de bois) et de CAT (séquestration du carbone) ont été utilisées pour fournir une comparaison économique des stratégies d'adaptation. Les critères du BASI de Faustmann et de Hartman sont adaptés au contexte déterministe, or MATHILDE est conçu pour simuler la croissance des forêts de manière stochastique *via* la méthode de Monte Carlo. Les critères du BASI ont donc été adaptés au cadre stochastique, en développant le BASI à double pondération (*double-weighted LEV*) afin d'estimer le BASI espéré. L'analyse de l'impact des décisions d'adaptation sur la séquestration du carbone a été développée en considérant trois méthodes différentes de comptabilisation du carbone (*i.e.*, la valeur marchande, la valeur tutélaire et le coût social du carbone). La maximisation du BASI a permis d'identifier les meilleures stratégies d'adaptation d'un point de vue économique. Les résultats ont montré que si la diversification réduit la perte de volume de bois due au risque sécheresse et augmente le BASI, elle réduit également le stockage du carbone. Il convient donc d'envisager des compromis entre le bilan financier et le bilan carbone. En ce qui concerne la production de bois (*i.e.*, le volume récolté) et la valeur économique (BASI), une combinaison de différentes stratégies peut être plus bénéfique pour le propriétaire forestier que chaque stratégie considérée séparément (*i.e.*, effets synergiques).

Les deux premiers chapitres se sont concentrés sur le risque de dépérissement induit par la sécheresse, bien que les peuplements forestiers puissent être affectés par plusieurs risques naturels au cours d'une même révolution. En effet, en France, la sécheresse et les tempêtes de vent sont les deux risques abiotiques les plus dommageables. C'est pourquoi, dans le **troisième chapitre**, l'impact cumulé des risques de dépérissement induits par la sécheresse et les tempêtes de vent a été étudié. C'est la première étude qui examine simultanément et d'un point de vue économique ces deux risques, ayant des récurrences indépendantes. Cette analyse est basée sur la même étude de cas (hêtre en région Grand-Est) et les mêmes méthodes qu'utilisées dans le deuxième chapitre (simulations de la croissance forestière *via* MATHILDE et CAT pour calculer le BASI à double pondération et utilisation des trois méthodes de comptabilisation du carbone). Les mêmes stratégies d'adaptation ont également été testées, car la diversification peut tout autant permettre de faire face aux dommages causés par les tempêtes. Des simulations ont été réalisées sous différentes récurrences de risques sécheresse et/ou tempête. Les résultats généraux étaient identiques que ce soit en considérant le risque sécheresse avec ou sans risque tempête : la diversification augmente la production de bois et le BASI, mais réduit le stockage du carbone. Les deux risques, ainsi que les stratégies d'adaptation ont montré certaines synergies en termes de production de bois et de valeur économique (BASI). Toutefois, la maximisation du BASI a montré que la prise en compte des deux risques influe sur les conclusions et les recommandations, par rapport à l'étude de chaque risque séparément : le meilleur scénario économique dépend du scénario climatique, du(des) risque(s), du taux d'actualisation et du prix du carbone considérés. Enfin, les résultats ont montré que des compromis entre le bilan financier et le bilan carbone (adaptation *vs*. atténuation) sont possibles.

Les trois premiers chapitres ont porté sur l'adaptation des forêts par le changement des pratiques sylvicoles (*i.e.*, adaptation basée sur la gestion forestière), en comparant différentes stratégies à l'échelle régionale. Un autre moyen d'aider les propriétaires forestiers à faire face au risque de dépérissement des forêts induit par la sécheresse est le développement de contrats d'assurance forestière (*i.e.*, adaptation basée sur les mécanismes de marché). Par conséquent, le dernier et **quatrième chapitre** propose un contrat d'assurance permettant la couverture des pertes économiques dues au risque de dépérissement des forêts induit par la sécheresse. Ce contrat, basé sur le principe de l'assurance indicielle, est déterminé à l'échelle nationale. L'efficacité des contrats d'assurance pour lisser les fluctuations de revenus a été étudiée en simulant des niveaux de productivité annuelle de deux essences majoritairement répandues dans les forêts françaises, à savoir le hêtre et le chêne. Les simulations ont été réalisées à l'aide du modèle CASTANEA, sous climat de référence (1960-2015) du système de ré-analyse SAFRAN. Différents indices de sécheresse avec des niveaux de complexité différenciés ont été testés et comparés. Ces indices vont des plus simples, basés sur les précipitations cumulées comme l'indice de précipitation standardisé (SPI), aux plus complexes, basés sur le stress hydrique comme l'indice de stress hydrique du sol (SWS). Des simulations ont été réalisées pour calibrer différents contrats d'assurance. Les régimes d'assurance ont été optimisés et testés. Les résultats ont montré que si les contrats d'assurance optimaux offrent un faible gain sur le revenu équivalent certain et un risque de base élevé (*i.e.*, l'absence de corrélation entre le revenu et la réalisation de l'indice), ils compensent une partie importante des pertes. La qualité du contrat n'est pas proportionnelle à la complexité de l'indice. Enfin, nos résultats préliminaires n'ont pas montré d'avantage évident à différencier les contrats d'assurance en fonction de l'essence d'arbre. Une discussion portant sur les perspectives offertes par les résultats de cette première approche clôt ce chapitre.

Principaux résultats et conclusion

Pour les études de cas considérées et sous certaines hypothèses, cette thèse a donc fourni les principaux résultats suivants. Premièrement, les résultats ont prouvé que l'adaptation est pertinente pour faire face au risque de dépérissement des forêts induit par la sécheresse : l'adaptation, qu'elle soit basée sur la gestion forestière ou sur les mécanismes de marché, fournit toujours le meilleur scénario par opposition au *statu quo* d'un point de vue économique. En d'autres termes, les bénéfices sont plus élevés que les coûts de mise en œuvre de ces nouvelles options de gestion ; ou l'utilité du propriétaire forestier avec assurance est plus élevée que son utilité sans assurance. Deuxièmement, la combinaison de stratégies d'adaptation basées sur la gestion forestière s'est révélée être un moyen pertinent pour adapter les forêts face à un risque croissant de dépérissement induit par la sécheresse. La combinaison de différentes stratégies peut donc être plus bénéfique pour le propriétaire forestier que d'établir chaque stratégie séparément (synergie *vs.* additionnalité) (Chapitres I à III). Cependant, toutes les options d'adaptation ne semblent pas pertinentes : les efforts d'adaptation peuvent augmenter la vulnérabilité des arbres et/ou induire des coûts plus élevés que les bénéfices dans certaines conditions, correspondant à une mauvaise adaptation (Chapitres I à III). Dans le même ordre d'idées, si l'assurance forestière contre le risque de dépérissement induit par la sécheresse reste une option, le faible gain des contrats actuels peut ne pas apparaître suffisant pour inciter les propriétaires forestiers à adopter ces dits contrats (Chapitre IV).

Enfin, l'adaptation au risque de dépérissement des forêts induit par la sécheresse est une question importante, qui nécessite des études complémentaires. Tout comme les forêts doivent s'adapter à la diminution de la disponibilité en eau (« adaptation pour les forêts »), les forêts sont nécessaires à l'adaptation au changement climatique : protection des ressources en eau ou encore amoindrissement du risque de désertification, entre autres services écosystémiques (« forêts pour l'adaptation »). En effet, alors que certains pourraient affirmer que « plus d'arbres implique moins d'eau », et que « l'absence d'eau implique celle des forêts », d'autres pourraient soutenir que « l'absence de forêt implique l'absence d'eau » (sécurité hydrique *vs.* couverture forestière). D'un point de vue plus décisionnel, dans le but de promouvoir la meilleure stratégie pour faire face au risque de dépérissement induit par la sécheresse, cette thèse montre l'importance de l'interconnexion entre différents domaines (écologie et économie) et de la prise en compte de la multifonctionnalité des forêts (production de bois et séquestration du carbone dans ce cas). Cette thèse prouve également l'intérêt et la nécessité de renforcer la collaboration entre différents secteurs (gestionnaires et chercheurs forestiers, ainsi que l'ensemble du secteur forestier) par des études plus approfondies, notamment sur la mise en œuvre des pratiques sylvicoles ainsi que par davantage d'analyses multicritères et multirisques. Jusqu'à présent, les sciences sociales ont été négligées comparativement aux approches techniques dans les études sur l'atténuation et l'adaptation au changement climatique en recherche forestière. Les sciences sociales ont toutes leur place pour compléter les sciences expérimentales dans les études climatiques. La recherche future devrait donc continuer dans cette direction, afin d'étendre et renforcer ce lien.

Abstract: Forests are ecosystems that play an important role in the adaptation of the society to climate change. They provide ecosystem services that contribute to human well-being and reduce social vulnerability. Presently, the pace of climate change is accelerating too fast for the natural and spontaneous forest adaptation process to offset many negative impacts of climate-induced changes, such as increased frequency, duration, and intensity of mean and extreme natural events like severe drought events. In France, the extreme drought events of 1976, 2003 and 2018 caused great damage to the forest, both immediately and long after the drought episodes. Private owners can protect their forests through adaptation strategies. Different management-based adaptation strategies are recommended in order to improve the water consumption efficiency of the forest stand and thus its resistance to drought risk. Market-based strategies may be another option. Four types of adaptation strategies were tested and compared, from an economic perspective, in this thesis. These are: incremental (reduction of rotation length and reduction of stand density), transitional (composition diversification and structure diversification) and transformational (species substitution) management-based adaptation as well as a market-based adaptation (index-based insurance). For that purpose, outputs from forest growth models were used as inputs for forest economics analysis, and an index-based insurance model was developed and simulated. The main results of this thesis, for the considered case studies and under some assumptions, can be summarized as follows. First, the results proved that adaptation is a relevant strategy to mitigate drought-induced risk of dieback by the implementation of either management-based adaptation or market-based adaptation. Second, combining different management-based adaptation strategies appeared as a relevant way to adapt forests in a context of an increasing drought-induced risk of forest dieback. Indeed, the combination of different strategies was found to be more beneficial for the forest owner than each strategy implemented separately. However, not all adaptation options appeared effective, *i.e.*, maladaptation. Finally, while forest insurance contracts covering drought-induced risk of forest dieback could be a relevant market-based option, small gains associated with current contracts are likely to prevent forest owners from adopting such insurance products.

Keywords: Forest; Adaptation; Drought; Carbon; Economics; Risk.

Résumé : Les forêts sont des écosystèmes qui jouent un rôle important dans l'adaptation de la société au changement climatique. Elles fournissent des services écosystémiques qui contribuent au bien-être humain et réduisent la vulnérabilité sociale. Or, le rythme du changement climatique s'accélère, en provoquant l'augmentation de la fréquence, de la durée et de l'intensité des événements naturels, notamment des épisodes de sécheresse extrême. En France, les épisodes de sécheresse extrême de 1976, 2003 et 2018 ont causé d'importants dommages à la forêt, à la fois immédiatement mais aussi durant plusieurs années. Les propriétaires privés peuvent protéger leurs forêts grâce à de multiples stratégies d'adaptation. Différentes stratégies d'adaptation basées sur la gestion forestière sont recommandées afin d'améliorer l'efficacité de la consommation d'eau du peuplement forestier et donc sa résistance au risque sécheresse. Le partage des risques peut être une autre option *via* l'assurance pour la couverture des pertes économiques. Quatre types de stratégies d'adaptation ont été testés et comparés d'un point de vue économique dans cette thèse : l'adaptation incrémentale (réduction de la durée de la révolution et réduction de la densité du peuplement), l'adaptation transitoire (diversification de la composition et de la structure) et l'adaptation transformante (substitution d'espèces) basées sur la gestion forestière, ainsi que de l'adaptation basée sur les mécanismes de marché (assurance indicielle). Pour cela, les données de sortie de modèles de croissance forestière ont servi de données d'entrée à l'approche économique. Un modèle d'assurance indicielle a aussi été développé et simulé. Pour les études de cas considérées et sous certaines hypothèses, cette thèse a donc fourni les principaux résultats suivants. Premièrement, les résultats ont prouvé que l'adaptation est pertinente pour faire face au risque de dépérissement des forêts induit par la sécheresse, qu'elle soit basée sur la gestion forestière ou sur les mécanismes de marché. Deuxièmement, la combinaison de stratégies d'adaptation basées sur la gestion forestière s'est révélée être un moyen pertinent pour adapter les forêts. La combinaison de différentes stratégies peut donc être plus bénéfique pour le propriétaire forestier que d'établir chaque stratégie séparément. Cependant, toutes les options d'adaptation ne semblent pas pertinentes, correspondant à une mauvaise adaptation. Dans le même ordre d'idées, si l'assurance forestière contre le risque de dépérissement induit par la sécheresse reste une option, le faible gain des contrats actuels peut ne pas apparaître suffisant pour inciter les propriétaires forestiers à adopter ces dits contrats.

Mots-clés : Forêt ; Adaptation ; Sécheresse ; Carbone ; Economie ; Risque.