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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 paper.

Keywords: Drought; Forest; Index insurance.

JEL codes: D01 (Microeconomic Behavior: Underlying Principles), G22 (Insurance, Insurance Companies, Actuarial Studies), Q23 (Forestry), Q54 (Climate, Natural Disasters and their Management, Global Warming).

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 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, through a constant relative risk aversion (CRRA) utility function and three different relative risk aversion coefficient (0.5, 1, 2). 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 1.

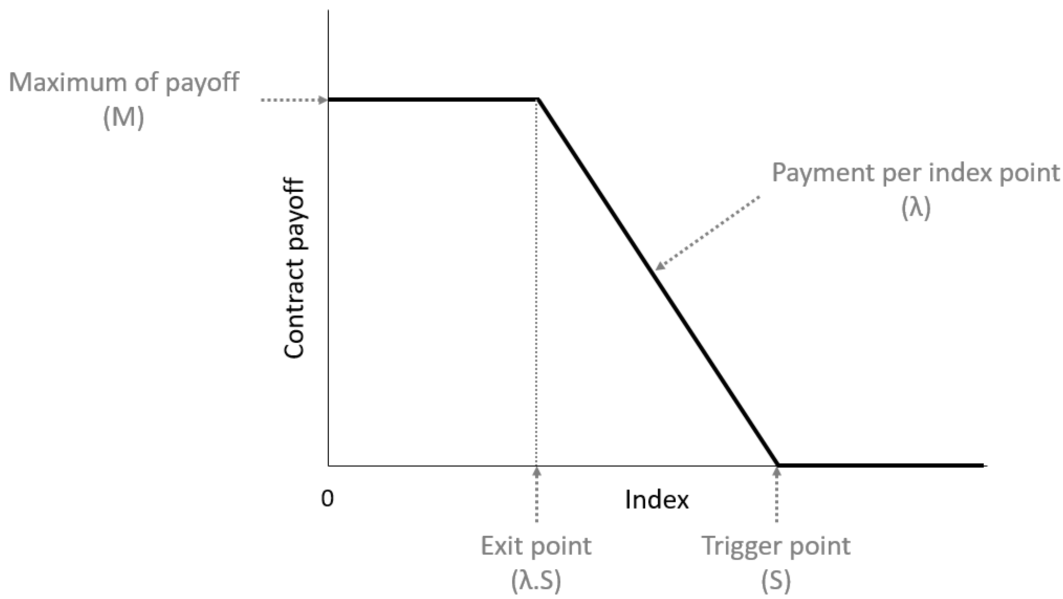

Figure 1: Payoff structure of an index-insurance contract (adapted from Vedenov and Barnett, 2004).

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[1] 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:

(2)

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

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

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 1.

Table 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_o) 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 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:

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

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

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 and the relevance 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 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 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 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 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 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_o, 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_o	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 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 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 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 2). However, a common result is the low gain in CEI (Table 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 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 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 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 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 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_0	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 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_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 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 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 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_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 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 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_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 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 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_{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 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 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_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 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 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_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 100-9000 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	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