Index insurance to cope 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 to forest production losses. In this context, we developed an *ex-ante* index-based insurance model to cope with drought-induced risk of forest decline. We applied it to beech and oak forests in France. We defined and then compared different indexes from simple ones relying on rainfall indexes to complex one relying on functional modelling of forest water stress. After the calibration of the contract parameters, an insurance scheme is optimized and then tested. We showed that optimal insurance contracts had low gain of certain equivalent income, provide high compensation and high basis risk. The best contract was not proportional to the complexity of the index. There was no clear advantage to differentiate or not the contract by species. Results are discussed highlighting the perspectives of this first approach.

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).

I- Introduction

In Europe, climate change increases temperature and reduces precipitation, stressing then the drought-induced risk of forest dieback (Bréda and Badeau, 2008). The exceptional drought in 2003 was associated with a heat wave that caused great damage on French forests (Bréda *et al*., 2006). In 2008, drought was stronger in intensity and area impacted than in 2003 (Buras *et al*., 2020). Forest damage due to extreme drought events are various: reduced growth, defoliation, and mortality. This loss of timber production results in severe socio-economic impacts for forest owners. In light of these impacts, Fuhrer *et al.* (2006) highlighted the need of adaptive management and new insurance tools for forests.

Several 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. The reduction of density, the reduction of rotation length, the substitution by a better-adapted tree species, or the increase of stand diversity are some of them (Spittlehouse and Stewart, 2003).

Another strategy is risk-sharing through insurance, which are relevant for public policy. Moreover, in a context of international agreements that highlight forests to cope with the effects of climate change, recommendations are made to use insurance as a vehicle to finance climate resilience and adaptation by OECD (2015) as well as on the Global Agenda Council on Climate Change (2014), 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 of disaster occurrence. In lots of countries around the world (China, New-Zealand, USA, Germany, France, Portugal, Spain, *etc*.) it is then possible to insure forest against natural events (Brunette *et al*., 2015). The most widespread insurance contract worldwide was for forest fire, which was also the first hazard insured (Kaul, 1928). However, the adoption of insurance is very different from one country to another. In France, insurers currently supply contracts against fire and/or storm to forest owners. Only 2% of the French private forest owners are insured, which represents 4% of the French forested area (Dossier Sylvassur, 2013). Very low penetration rate also characterizes German, Spain and Slovakian markets. In countries like Denmark and Sweden forest insurance against storm is a more common practice with 68% and 90% of the private forest owners who are insured (Brunette and Couture, 2008). In order to explain these differences, Loisel *et al.* (2020) suggest several explanations: mandatory insurance like in Norway *vs*. voluntary one like in France, conditional public assistance in Denmark *vs*. non-conditional one in France and 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 worldwide proposes to insure drought-induced risk of forest dieback. Traditionally, drought is insured against in the agricultural sector through index-based insurance. However, because of climate change, drought becomes a relevant issue in the forestry sector. Index insurance seems to be a relevant and well-adapted tool for forest, since the index can be defined for a certain level of stress, here for extreme drought event (not every kind of annual drought). In this context, the objective of this paper is to design and test an index-based insurance built to cope with drought-induced risk of forest dieback on French forest data. In that purpose, we develop an *ex-ante* index-based insurance contract and simulate its effectiveness to smooth forest owners' income. We simulate annual forest productivity for two representative broadleaf tree species of France, beech and oak, by using the forest growth model CASTANEA driven by historical climate series (1960-2015) taken from the SAFRAN reanalysis system (Vidal *et al*., 2010). We define and then compare different indexes from the most simple, cumulative rainfall and the Standardized Precipitation Index (SPI), to more complex indexes, based on water stress, the so-called soil water stress index (SWS) (Guillemot *et al*., 2017). Simulations are performed to calibrate the insurance contract. Then, an optimal insurance scheme is optimized and then tested. We show that optimal insurance contracts have low gain of certain equivalent income (CEI) and high basis risk, and compensate a high part of losses. The best contract is not proportional to the complexity of the index. Finally, our first results do not present clear advantage to differentiate or not the contract by species.

The rest of the paper is structured as follows. The next section reviews relevant studies on forest insurance and agricultural index-insurance. The material and the methods are presented in Section 2. Section 3 provides the results, which are discussed in Section 4. Section 5 concludes.

II- Literature review

This article is at the interface between two research areas: One dealing with forest insurance, without referring to index-based insurance, and another one studying index-based insurance, without considering forest area.

The literature on forest insurance deals with several streams. The first one deals with actuarial approaches that aim to determine the insurance premium, mobilizing different “pricing” methods. In this vein, 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 found a gross insurance premium from 0.77 EUR/ha at age 0 for an insured area of 140,000 ha to 4429 EUR/ha at age 70 for an insured area of 14 ha, highlighting the main role of the stand age and the total insured area. Some papers follow with for example Pinheiro and Ribeiro (2013) on forest fire insurance in Portugal, Brunette *et al.* (2015) on forest insurance against multiple natural hazards in Slovakia, and

Sacchelli *et al*. (2018) in Italy. One of the main conclusion of this first stream of literature is the need to increase the insured area (to increase mutualisation and then to dilute the risk) in order to propose affordable insurance premium.

A second stream of literature tries to extend the classical insurance economics model proposed by Mossin (1968) with the specificities of the forest management issues. Brunette and Couture (2008) developed a theoretical model to predict insurance demand. It shows the potential negative impact of *ex-post* public compensation after disaster occurrence on the forest owners' insurance demand. Brunette *et al*. (2017a) proposed a theoretical model under risk and uncertainty to study the effect of including adaptation efforts in insurance contract on insurance demand. They showed that insurance is relevant to encourage (mainly risk-averse and uncertainty-averse) forest owners to adapt to climate change.

The third stream deals with the assessment of forest owners' demand for forest insurance. Brunette *et al*. (2013) were the first to assess the willingness to pay (WTP) for French forest owners in different scenarios regarding public compensation, and proved the negative impact of these compensations on WTPs. Other papers follow and estimate forest owners' WTP in 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 simultaneously real and hypothetical forest fire insurance choices demonstrating that real insurance decision significantly explains the hypothetical one. They also showed, in an experimental economics setting, that facing ambiguous risk increases the WTP for insurance.

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 take out an insurance contract. They proved that an *ex-ante* public transfer to the insurer, resulting in a reduced insurance premium, might increase insurance demand. Qin *et al.* (2016) proved the same result in China with an *ex-ante* public transfer to insured.

Concerning the index-based insurance literature, the principles of insurances based on meteorological index were initiated by Halcrow (1948) and developed by Dandekar (1977). Those products were initially proposed to help farmers to cope with agricultural risks and mainly implemented in developing countries (Skees *et al*., 1999; Mahul, 2001), where the limited installed infrastructures makes low transaction costs contracts even more interesting.

Index-based insurances consist in compensating farmers if an index defined from weather variables goes beyond a given threshold, in exchange for the payment of an annual insurance premium. Indemnity of traditional insurance requires the observation and the assessment by experts of the level of crop damage after a disaster. This induces a cost resulting in a high insurance premium and introduces asymmetry of information between the insurer and the insured farmer. For index-based insurance, meteorological data are independent of the principal and the agent. An observable index from meteorological data solves then this traditional moral hazard issue (Goodwin and Mahul, 2004), reduces the transaction costs and allows a quick payment of the indemnity (Alderman and Haque, 2007). Index allows focusing on one risk independently of the other conditions. Having a single index for a common disaster and then for many contracts, and not for a specified risk on a specific stand, reduces also the transaction costs and thus the insurance premium.

However, the main drawback of such contracts stem from the index imperfection, creating a lack of correlation between income and index realisation: the so-called basis risk (Skees, 2003). There is two types of basis risk: When forest owners receive an indemnity while they do not endure losses (type I), or when they endure losses without receiving an indemnity (type II). Imperfect insurances indeed show very low demand mainly due to various effects of such basis risk (Clement *et al*., 2018). The readability of the contract and simplicity of the index is also a challenge for distribution and diffusion of such contracts. One of the objectives of our paper is then to test different indexes from simple to more complex ones taking into account these aspects.

We thus propose a new method with an *ex-ante* index-based insurance to cope with an increasing risk in forest, drought-induced risk of dieback. To our knowledge, no study (i) deals with drought insurance in 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 in line with the first stream of forest insurance: We simulate data to compute the insurance premium and the optimal insurance contract, but through a different method. As in the paper of Holecy and Hanewinkel (2006), we consider different stand age.

III- Material and methods

1. Data

Because of the lack of historical data about locally observed annual forest growth, we simulated series of annual productivity of two representative broadleaf tree species of France, beech and oak, using 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 the evolution of the water and carbon fluxes and stocks (both aboveground and belowground) of the forest ecosystem, with processes simulated at time steps 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 includes some physiological responses to drought including the risk of decreased growth or even mortality related to water stress and shortage of carbohydrate reserves (Davi and Cailleret, 2017), and takes the specificity of each species into account.

CASTANEA requires weather data (global or photosynthetically active radiation, air temperature, relative air humidity, wind speed, precipitation) as inputs. We used the 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, and overall represent 8588 pixels of 8×8 km each. Following Cheaib *et al.* (2012), distributed soil 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 to provide measures of plant available water capacity and soil depth (Badeau *et al.,* 2010).

In order to capture only the climatic variability, 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 age linked to an initial biomass in gC/m^2, in order to consider stand age and biomass variability. Three pairs of age-biomass (year-gC/m^2) are considered: 40-5000, 70-7000 and 100-9000. The annual output data were the productivity 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 annual series of average wood prices for beech and oak from the *Comptes de la Forêt* of the Observatory for Forest Economics (OLEF, BETA) in France. We used wood prices for a diameter class of 71-80 cm corresponding to commercial timber class in the market. Due to high damage of the Lothar storm in 1999, wood prices were so low, and selling so limited that they were not recorded and result as a missing data in databases. We computed wood prices for 2000 using species price discounts from the French National Forest Office (ONF): 85% for oak and 50% for beech.

2. Insurance policy design

We started with a simple framework with the following assumptions. The representative agent is a private forest owner that aims to reduce the effect of drought risk in their stand. A private insurer offers a same contract at each representative agent for the whole France. Each SAFRAN point represents the stand of an agent. In order to compare the gain of certain equivalent income (CEI) between taking out or not insurance, the utility with and without insurance is computed for each agent. The agent takes out insurance as long as the gain of CEI is positive.

2.1. Indemnity schedule

Indemnity schedule was defined by three parameters according to the framework of 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.

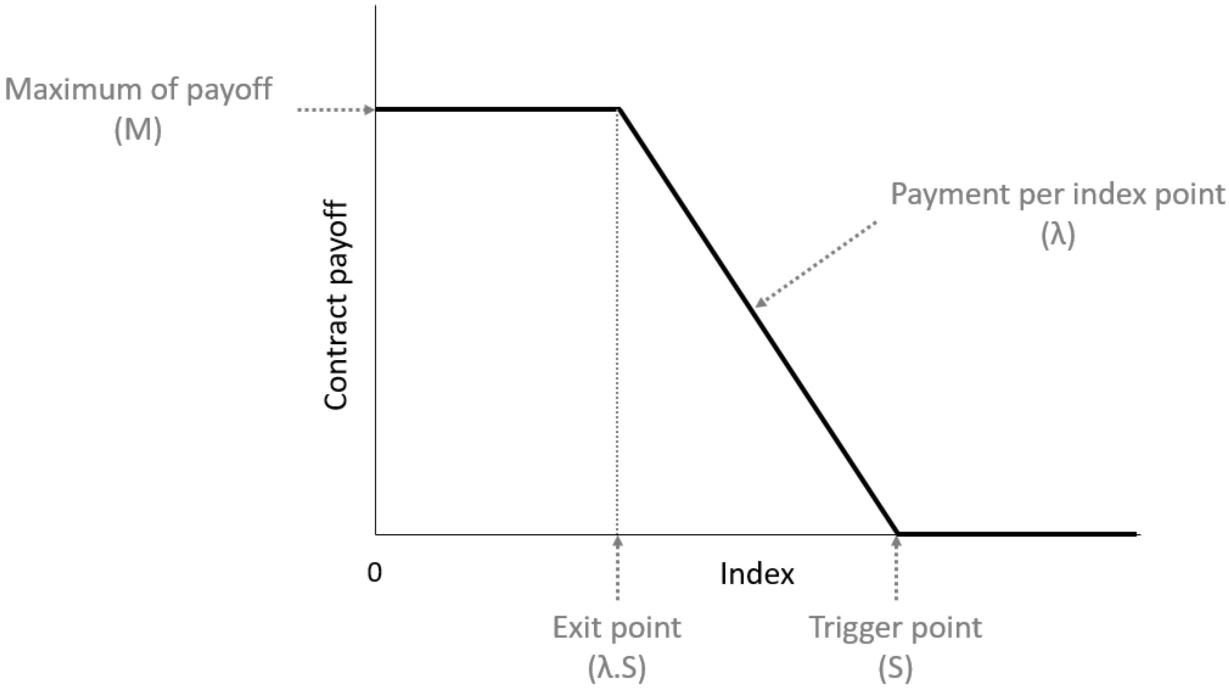

Figure 1: Scheme of the payoff structure of an index-insurance contract (adapted from Vedenov and Barnett, 2004).

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

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

2.2. The tested indexes

To assess the interest of an index, we defined, tested and then compared different indexes from simple ones (basic rainfall index) to complex one (drought index).

The first one is 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, that is the overall growing period.

The second index is the standardized precipitation index (SPI), which is a slight improvement of the cumulative precipitation and widely used to characterise meteorological drought. SPI quantifies observed precipitation as a standardized departure from the mean of the considered period. We computed the SPI-three months (SPI3) and the SPI-six months (SPI6), using the same period of cumul than CP3 and CP6. However, SPI is only a measure of water supply. The index does not consider the evapotranspiration, and thus the effect of temperature on moisture demand and availability.

We therefore considered a more complex index, the integrated annual soil water stress Index (SWS) (Guillemot *et al.*, 2017), taking into account water supply (rainfall and soil water capacity) and demand (canopy and soil evapotranspiration). The index also considers some vegetation characteristics such as the water stress impact on the stomatal[1] closure. The idea of considering this SWS index is that forest productivity depends on the satisfaction of tree needs for soil water resource. It is acknowledge that

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

soil water content has low effects on plant functioning until a certain threshold (Granier *et al.,* 1999), we thus applied a threshold on the available water content in the soil (AWC) of 40%, representing the conditions under which tree starts to regulate water consumption and thus has difficulties to grow and survive (Lebourgeois *et al.*, 2005). Annual SWS index is then the sum of all the daily tree water stress during the growing season (*i.e.* 200 days), which is computed by CASTANEA model as follows:

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

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: $\text{SWS}_{\text{beech}}$ and SWS_{oak}.

The framework of Vedenov and Barnett (2004) was based on an index of water availability on the soil: The indemnity increases with the decrease in the index (up to the maximum); and the index is not less than zero. In the way to follow this framework, we applied a transformation to the SPI and SWS values. The range of SPI went from [-5; +5.5] at the beginning to [0; 10.5] after transformation to have only positive values. The range of values of SWS kept the same with [0; 200], but the transformation led having values close to zero corresponding to the highest level of drought, instead of 200 at the beginning. The final range of value is summarised in Table 1:

	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
$\text{SWS}_{\text{beech}}$	0	123.0	168.5	28.4
SWS_{oak}	0	125.4	172.7	29.1

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

2.3. Optimisation of insurance contract

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

$$W_0(t) = K_0 + w(t) \quad (3)$$

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

where K_0 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.* $\tau = 0$).

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 or the plantation to the final harvest of the forest stand.

Second, we used a Constant Relative Risk Aversion (CRRA) utility function U, which is commonly used in the literature to represent individual insurance behaviours, particularly those of forest owners (Sauter *et al.*, 2016; Brunette *et al.*, 2017b), in order to compute the variation of CEI, as follows:

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

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

where $EU(\bar{W}_0)$ the expected utility of the vector of income realizations $(\overline{W_0})$ without insurance, $EU(\bar{W}_{ins})$ 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 optimise 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 interest to differentiate insurance contracts by species, we then computed optimal insurance contract for a baseline corresponding to a unique contract, and one for each species separately (beech and oak).

IV- 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 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 indexes, 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 of CEI are very low. Gain of CEI decreases with the basis risk type II.

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

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 euro) compared to the initial one (CEI_0, in euro), and the annual premium for each index for the baseline in euro (unique contract) and the species-specific contracts (beach and oak) considering an age-biomass class of 70-7000 and a relative risk aversion coefficient of 1.

To assess the interest of an index and to 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 with 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 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 losses' part compensated by indemnity, going from 26.6% (with SWS) to 99.5% (with SPI6). However, we can see that a high losses' part compensated by indemnity is linked to a high basis risk type II (close to 50% cases). Six month-indexes (CP6, SPI6) present higher losses compensated, a lower basis risk type I, and a higher basis risk type II than three month-indexes (CP3, SPI3). The more complex index, SWS, shows lower losses compensated, a higher basis risk type I, and a lower basis risk type II than the other indexes.

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 3: Percentage of financial losses compensated by indemnity (Comp_loss), percentage of basis risk type I (BR_I) and type II (BR_II) 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 (beach and oak) considering an age-biomass class of 70-7000 and a relative risk aversion coefficient of 1.

More in details, to assess the interest 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 indexes in terms of maximum of gain of CEI and compensated losses, and minimum of premium and basis risk for the three age-biomass classes. The results show that no index provides the best level for all the parameters and all age-biomass classes. There is variation among indexes (an index can be good for some criteria and bad 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 interest to provide species-specific contracts based on SPI3, regarding age-biomass classes. Except this, there is no clear advantage to differentiate or not the contract by species: Results depends on the considered index, age-biomass class and criterion.

	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
Compens_loss (%)	B		B		B; O			B	O	B	B	B	B	B; O	B
Basis_risk_I (%)			B		B		O	B		B	B	B; O	B	B; O	B
Basis_risk_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

Table 4: Comparison between the baseline and the species-specific contracts for the different indexes 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, a higher percentage of financial losses compensated by indemnity (Comp_loss), a lower percentage of basis risk type I (BR_I) and type II (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 indexes 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).

V- Discussion and perspectives

1. Optimal insurance contracts have low gain, and provide high compensation and high basis risk

The heterogeneity of optimal insurance contracts shows the importance to test different indexes and to consider different parameters (species, age-biomass, relative risk aversion coefficient) (Table 2). However, a common result is the low gain of CEI (Table 2). This result was also demonstrated in the paper of Leblois *et al.* (2014) testing an *ex-ante* insurance model for agriculture: This low gain might be explained by the cost observed for implementing such insurance policies. Here, our low gain probably comes more from a high basis risk (Clement *et al*., 2018).

SWS provides the best contract as for the baseline (unique contract) as for the two species, but with the lowest gain of CEI, the highest premium, and the lowest part of losses compensated by indemnity. In addition to this, while index like SPI provided almost full compensation of losses, this was linked to a high part of losses not compensated by an indemnity (basis risk II) (Table 3), which is the worst risk between the two basis risk, because it undermines the credibility and sustainability of the system. The basis risk I, which can induce a higher premium, was low in our results (Table 3). There is then a trade-off between having a good correlation between the index and the losses and having a good part of compensated losses. In the same vein, the heterogeneity of our results showed the difficulty to define a “perfect” index (Table 4).

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

There was no clear advantage to differentiate or not 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 variability in terms timber production and drought tolerance.

Second, French insurers applied multiplicative coefficients to the insurance premium in area considered as riskier than others, *e.g.* Mediterranean regions for fire risk. In the same vein, they also excluded some regions considered as uninsurable. In line with 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 need or not 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.

3. Other perspectives of the study

Our results come from a first approach that will be improved by the following items.

First, the insurance premium is normally higher than the expected indemnity. Indeed, our insurance model was in a case of an actuarially fair insurance. The classical insurance economics literature (Mossin, 1968) shows that unfair insurance premium reduces the level of insurance. We can thus expect that in our case, testing a loading factor of 10%, as in the studies of Brunette and Couture (2018) and Loisel *et al*. (2020), will increase insurance premium and reduce thus the level of insurance.

Second, insurance contract could be adapted to the context of increasing risk by climate change to avoid the increase of insurance premium over time by insurers, resulting in the decrease of insured on the market, and thus to 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 as exceptional drought has to be flexible. This will result in less regular payoff but for high damage. To test such contracts, we will perform index and insurance contract simulations under different climate change scenarios by accounting for the variability between global climate models that produce climate projections. 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) that have been downscaled and bias corrected on the SAFRAN grid used for the simulation presented earlier (Fargeon *et al*., 2020). These data were made available for five different combinations of global-regional climate models, in order to account for uncertainties related to the type of climate model (Fargeon *et al*., 2020).

Third, only wood prices for a diameter class of 71-80 cm were used for this first approach. As we tested different age-biomass class, 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 in the market. We have these wood prices series from the *Comptes de la Forêt* of the Observatory for Forest Economics (OLEF, BETA) in France.

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

VI- Conclusion

Since 2017, French State is no longer involved in insurance system: Only private sector provides insurance contracts. However, the low part of insured forest owners shows the need to propose new and suitable products, even more in the context of climate change. Dealing with increasing drought-induced risk, index-insurance may be a good tool in climate risk management to compensate financial losses.

The originality of our study was to investigate an *ex-ante* index-insurance model for forest disturbances testing different indexes. We showed that optimal insurance contracts have low gain of CEI and provide high compensation and high basis risk. There was no clear advantage to differentiate or not the contract by species. But including a regional differentiation on the species-specific insurance contract can improve the results. This first approach will be improved, in particular with the inclusion of future climate data.

This study shows many further research perspectives for adaptation to climate change. Insurance can be a tool to give incentives for forest adaptation (Brunette *et al.*, 2017a). Forest owners do not use sufficiently silvicultural practices to adapt to climate change (Andersson and Keskitalo, 2018). Therefore, an idea can be to encourage forest owners to adopt new forest management, if not they will receive a lower payoff (or pay a higher premium) in case of damage. Another extension could be to integrate carbon into timber insurance as suggested in some papers (Subak, 2003; Wong and Dutchke, 2003; Figueiredo *et al.*, 2005; Grover *et al.*, 2005). Finally, drought induces inconspicuous damage at first sight resulting in complex dieback later. This complex effect can come from a set of secondary risks such as pests' attack (Desprez-Loustau *et al*., 2006) and fire (Stephens *et al*., 2018), which can result in the imperfect correlation between the index and the stand damage. Working with simulated data, we cannot represent this effect on our results. When data will be available, testing our model on observed data can be interesting to think about composite indexes integrating this complex effect. In addition to this, insurance can cope with many risks and linking two dependant risks such as drought and fire insurance can be an idea, which is not currently done (only independent risks: storm and fire).

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Supplementary material

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

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.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 euro) compared to the initial one (CEI_0, in euro), the annual premium (in euro), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of basis risk type I (BR_I) and type II (BR_II) 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 (beach 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	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

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 euro) compared to the initial one (CEI_0, in euro), the annual premium (in euro), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of basis risk type I (BR_I) and type II (BR_II) 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 (beach and oak) considering an age-biomass class of 100-9000.

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

Species	Index	CEI_0	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.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 euro) compared to the initial one (CEI_0, in euro), the annual premium (in euro), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of basis risk type I (BR_I) and type II (BR_II) 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 (beach and oak) considering an age-biomass class of 40-5000 and a relative risk aversion coefficient of 0.5.

Species	**Index**	**CEI_0**	**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.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 euro) compared to the initial one (CEI_0, in euro), the annual premium (in euro), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of basis risk type I (BR_I) and type II (BR_II) 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 (beach and oak) considering an age-biomass class of 70-7000 and a relative risk aversion coefficient of 0.5.

Species	Index	CEI_0	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

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 euro) compared to the initial one (CEI_0, in euro), the annual premium (in euro), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of basis risk type I (BR_I) and type II (BR_II) 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 (beach and oak) considering an age-biomass class of 100-9000 and a relative risk aversion coefficient of 0.5.

C. Optimal insurance contract and effectiveness criteria of the insurance contract (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	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.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 euro) compared to the initial one (CEI_0, in euro), the annual premium (in euro), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of basis risk type I (BR_I) and type II (BR_II) 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 (beach and oak) considering an age-biomass class of 40-5000 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	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.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 euro) compared to the initial one (CEI_0, in euro), the annual premium (in euro), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of basis risk type I (BR_I) and type II (BR_II) 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 (beach and oak) considering an age-biomass class of 70-7000 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

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 euro) compared to the initial one (CEI_0, in euro), the annual premium (in euro), the percentage of financial losses compensated by indemnity (Comp_loss), the percentage of basis risk type I (BR_I) and type II (BR_II) 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 (beach and oak) considering an age-biomass class of 100-9000 and a relative risk aversion coefficient of 2.