An Economic Comparison of Prevention Strategies against Forest Pathogens

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Abstract

In this paper, we use a cost-benefit approach in order to compare existing treatments to prevent the invasion of three pathogens (*Hylobius abietis*, *Dothistroma septospora and Dothistroma pini*, *Heterobasibion annosum*) in Landes forest, in th South-West of France. Our results show that for *Hylobius abietis*, the prevention, either self-insurance (cypermethrin solution) or self-protection (fallow), appears to economically dominates the absence of prevention. For *Dothistroma septospora and Dothistroma pini* our results indicate that the treatment analysed, (mancozeb solution), is never economically relevant for the forest owner as it induces negative LEV. We compute the threshold value of the treatment for which the LEV becomes positive and thus the treatement could be considered. This value is 45% lower than the current one. Finally, for *Heterobasibion annosum*, we analyse various self-protection activities and we show that a local stump removal just after contamination is always more profitable than a systematic preventive treatment and that a fallow at the end of rotation better performs local stump removal if and only if the contamination occurs during the second thinning, when the forest is mature. Beyond the specifities of the case study, the paper proposes a methodology to analyse such problematic.

Keywords: forest pathogens, *Hylobius abietis*, *Dothistroma septospora and Dothistroma pini*, *Heterobasibion annosum*

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1 Introduction

As global changes arise, forest pathogens become an increasing threat for forest ecosystems. Climate change impacts forest health in both direct and indirect ways. On the one hand, temperature, solar radiation, rainfall and atmospheric CO_2 concentrations represent major direct drivers of forest productivity and forest dynamics (Scholes et al.[49]). On the other hand, climate changes influence insect populations dynamics and geographical displacement, such as population release by warmer winter temperatures (Bentz et al. [5]), as well as fungi development (Scholes et al.[49]), which both increase the risks of invasions in forest ecosystems.

This relationship is already supported by recent observations at global scale. In North America, widespread die-back events (high mortality rates at a regional scale) have occurred concomitant with infestation outbreaks (Hogg et al.[22]; Michaelian et al., [38]; Raffa et al., [44]) while, in Europe, an increasing incidence of diseases has been observed in many forests (FAO, [17]; Marcais and Desprez-Loustau, [37]). Between 1994 and 2005, about 8% of the European trees were attacked by pests and 5% by pathogenic fungi (Jactel et al. [26]). Overall, 57% of the forest damages has been caused by biotic hazards, of which 34% by insects, 19% by fungi and 4% by herbivorous mammals, while abiotic hazards has been responsible for 22% of the damages and anthropogenic hazards for 21% (Jactel et al. [24]). In Continental Europe, some species of fungi have benefited from milder winters and others have spread during drought periods from south to north (Drenkhan et al.[15]; Hanso and Drenkhan [20]). Projected increased late summer warming events will favour diffusion of bark beetle in Scandinavia, in lowland parts of central Europe and Austria (Jönsson et al.[28]; Jönsson et al.[27]; Seidl et al.[50]; in Scholes et al.[49]).

In France, 14% of trees are attacked each year by pests and 5% by pathogenic fungi. They generate 81% of the overall observed damages in forests, of which 61% are caused by insects and 20% by fungi (Jactel et al. [24]). Such risks are likely to increase in the near future as France is expected to undergo a temperature rise and an increased recurrence of major climatic events (Kovats et al.[32]). Yet, it has been demonstrated that a temperature rise leads to a raise of some biotic hazards (Rouault et al. [47]) while the increase in frequency and intensity of some natural hazards favors the development of pests and pathogenic fungi (Desprez-Loustau et al. [14]; Vanhanen et al. [53]; Berggren et al. [6]).

In addition to these climate factors, human activities are also likely to increase species displacement rates by intentionally or unintentionally dispersing individuals or propagules. In particular, the increasing globalization of trade facilitates the import of exotic species which may result in new biotic hazards (Desprez-Loustau [12]; Desprez-Loustau et al. [13]; Roques et al. [45]).

In this context, it has been shown that prevention is one of the most effective economic strategy for managing invasive forest pathogens (Parker and Gilbert [40]; Klopfenstein et al. [30]). Besides conventional chemical treatments, possible responses to prevent the invasion of pathogens on forests include the preference for species better adapted, the selection of tolerant or resistant families and clones in pure stands (Jactel et al.[25]), the preference for mixed-species forests as well as the use of fallow at the end of a forest rotation.

At management scale, the effective implementation of these solutions depends on their costs and their potential benefit. On the one hand, prevention options always come with a cost, at least in a first stage. On the other hand, forest pathogens can reduce economic profitability of forests by increasing tree mortality, decreasing forest productivity or timber quality as well as reducing the opportunity to use forest areas for recreation and tourism. In addition, pathogens invasion can have a negative impact over biodiversity by increasing species competition and can reduce the ability of forests to store carbon (Klopfenstein et al. [30]). Yet, the economic consequences of these impacts are difficult to assess since ecosystem services provided by forests are usually not monetarized. However, considering a reduction of 2.8% to 5.6% of the value of ecosystem services due to the damages caused by pathogenic fungi, Sache et al. [48] estimate that such damages result in a 400-800 M€/yr loss for French forests. At global scale, other economic assessments of forest pathogens implications include Liebhold et al. [35]; Leuschner et al. [34]; Price et al. [42]; Pye et al. [43]; Baskin [3]; Rosenberger and Smith [46] for U.S forests and Zwolinski et al. [54] for South Africa forests.

Up to now, prevention strategies within the forest sector have been analysed from the economic point of view through two different methodological frameworks. Reed [**?**], [**?**] analysed how prevention impacts the optimal harvesting age within an optimal harvesting age model frameworks. To do so, he assumes that a forest owner implement each year prevention activities in order to prevent fire risk. Optimizing the intertemporal benefits from the sale of forest products, he showed that such a prevention strategy increases the optimal harvesting age. Using a similar approach, Amacher et al. [1] developped a theoretical model to analyse the impacts of prevention on the optimal harvesting age. They assume that fire-risk prevention activity was implemented just once at some point during the forest rotation. Using simulation, they showed that prevention activity increases the optimal harvesting age. Following a prevention economics approach, Brunette and Couture [9], [10] analysed the impact of public financial assistance provided after a storm on the incentives of a forest owner to implement prevention activities. They show that such an assistance can reduce the incentives of forest owners to invest in prevention.

It therefore appears that (1) the analysis of prevention in forest sector has resulted in very few papers, (2) the existing papers do not concentrate on pathogenic risks and (3) they do not analyse the impacts of prevention on the economic value of the forest, *i.e.* from a purely financial point of view.

In this paper, we propose to fill these gaps by questioning the relevance of pathogens prevention from an economic perspective. Our objective is to compare the impact of several prevention strategies on the financial value of the stand. To do so, we develop a forest economics methodology within a cost-benefit framework based on land expected value (LEV) in order to compare existing treatments to prevent the invasion of three pathogens. We focus on the Landes forest case study. The Landes forest is located in Aquitaine, South-West of France, and is almost exclusively composed of Maritime pine (*Pinus pinaster*). We focus our analysis on three pathogens regarding two mains criteria. (1) We choose to analyse impacts of pathogens which were barely studied up to now. (2) We choose pathogens which are already present in this forest and/or expected to arrive soon. Following these criteria, we selected three pathogens: one pest (*Hylobius abietis*) and two pathogenic fungis (*Heterobasibion annosum* and *Dothistroma septospora*).

Our results show that for *Hylobius abietis*, the prevention, either self-insurance (cypermethrin solution) or self-protection (fallow), appears to economically dominates the absence of prevention. For *Dothistroma septospora/pini* our results indicate that the treatment analysed, *i.e.* self-protection (mancozeb solution), is never economically relevant for the forest owner since it induces negative LEV. The threshold price of the treatment for which the LEV becomes positive is 45% lower than the current one. For *Heterobasibion annosum*, we tested four strategies: a Rotstop solution, local stumps removal after contamination, total stumps removal after contamination, fallow after contamination. We show that a local stump removal just after contamination is always more profitable than a systematic preventive treatment and that a fallow at the end of rotation is more profitable than local stump removal if and only if the contamination occurs during the second thinning, when the forest is mature.

Overall, beyond the specifities of the case study, the paper proposes a methodology to analyse this problematic.

The paper is organised as follows. Section 2 describes the materials and method. Results are presented in Section 3. Finally, Section 4 discusses the results and Section 5 concludes.

2 Materials and method

2.1 Definitions

Prevention

The analysis of prevention strategies from an economic perspective was first proposed by Ehrlich and Becker [4] who defined two different prevention strategies called self-insurance and self-protection. Self-insurance is a preventive action which aims to reduce the damages in case of risk occurrence while self-protection reduces the probability of occurrence of the risk.

Risk and uncertainty

Uncertainty refers to a situation where the probability of occurrence of a disater is not well-known while risk refers to a situation in which probability of occurrence is known (Knight [31]). The probability of occurrence of some events may be difficult to estimate due to the lack or the scarcity of past occurrences, in this case only intervals of probabilities are available. In this paper we refer to risk whenever the associated probability is known and we refer to uncertainty whenever the probability and/or the amount of the damage is not known.

2.2 Economic Criteria

The forest owner is supposed to maximize his forest's Land-Expected Value (LEV) calculated as follows.

In a first step we calculate the Net Present Value (NPV) of costs and benefits for one rotation. The NPV is the present value of positive payments minus the present value of negative payments made at different points in time (Klemperer [29]):

$$NPV = \sum_{i=0}^{n} \frac{B_i - C_i}{(1+r)^i} \tag{1}$$

with B the benefits, C the costs, r the discount rate and n the rotation length.

In a second step, we compute the Land Expectation Value (LEV), defined as the sum of all NPVs:

$$
\begin{aligned}
LEV &= \sum_{i=0}^{n} \frac{B_i - C_i}{(1+r)^i} \times \frac{(1+r)^n}{(1+r)^n - 1} \\
&= NPV \times \frac{(1+r)^n}{(1+r)^n - 1} \qquad (2)
\end{aligned}
$$

To compute the LEV, we assume that all rotations are identical, *i.e.* same time horizon, same sequence of events within each rotation, and same net revenue associated with each event within each rotation. In addition, we assume that the prices and the forest productivity are constant over time. Using LEV presents two major advantages. First, it makes it possible to compare sylvicultural scenarios that come with different rotation lenghts. Second, it allows to distinguish the management of the current stand from that of future stand.

We assume $r = 3.5\%$. A sensitivity analysis is made on this parameter and presented in the discussion.

2.3 Case study

Geographical boundaries. We focus on the French "Massif Landais", which mostly consists in a plantation of Maritime pine (*Pinus pinaster*), for two main reasons. First, this forest is managed as a monoculture, a type of forest management resulting in a high sensitivity to phytosanitary problems (Jactel et al. [23]) as forest pathogens are often specific to a species and/or an age class. Second, the French "Massif Landais" had recently suffered from two major windstorms, Lothar in December 1999 and Klaus in January 2009. Such extreme climatic events are currently facilitating forest pathogen invasions *via* the accumulation of windfall on the soil. Therefore, the monoculture of Maritime pine in the "Massif Landais" appeared to be a relevant area to study forest pathogens.

Benchmark of sylviculture. The "Societé Forestière de la CDC (Caisse des Dépôts et Consignations)" defines a sylvicultural benchmark for a monoculture of Maritime pine. This benchmark gathers costs and benefits associated to this management practice as indicated in Table 1. This benchmark consists in a plantation of 1100 stems/hectare, a clearing at year 2 of the plantation, two thinnings (year 12 and 22) and a final harvest at year 35. We also consider management costs (covering machine maintenance for instance) for 39€/ha/year except for year 0. Although they do not appeared in the following table, they are considered for the calculation of Net Present Value.

For this benchmark, the density equals 500 trees/ha after the first thinning (year 12) and 321 trees/ha after the second thinning (year 22). In our model, we assume the rational profit-maximizer

Table 1: Net benefits of a monoculture of Maritime pine

Year	Operations	Net benef.	Density
0	Plantation	-900	1000
2	Clearing	-70	1000
12	Thinning	111	500
22	Thinning	684	321
35	Harvest	7228	0
NPV^{*}	$NPV_B = 816.86$		

*The NPV is computed considering the additionnal management costs of 39€/ha/yr.

forest owner wants to keep constant these densities.

The Net Present Value equals 816.86 €/ha (NPV_B in Table 1), and the Land Expectation Value (LEV) :

$$LEV_B = NPV_B + \left(\frac{NPV_B}{(1+0.015)^{35}} \times \frac{(1+0.015)^{35}}{(1+0.015)^{35}-1} \right) = 1166.91e/ha \quad (3)$$

In the rest of the paper, for each pathogen, we will first compare this LEV with those obtained when pathogenic risk is introduced. Then, we will compare LEV with and without prevention strategies when risks are introduced. This will help us to determine the most economically relevant strategy.

3 Results

We analyse separately each forest pathogen. For each pathogen, we compute LEVs without and with treatment. The treatment consists in prevention activity, *i.e.* either self-insurance or self-protection.

3.1 *Hylobius abietis*

Hylobius abietis is a little weevil spreading in France and causing important damages on young plantations. It develops under the bark of the host tree. A tree attacked by *Hylobius abietis* is necessarily lost. When the plantation occurs the year after the final harvest, which is the common practice, the probability of invasion is likely sure, therefore we assume a probability of invasion equal to 1. The associated damages are uncertain, ranging between 50 and 80% on a stand with no treatment. We consider that the damaged trees are not replaced, therefore only the non-damaged trees will finally compose final stand.

Two treatments are available. One consists in soaking the seedlings during the nursery stage in a solution containing a cypermethrin solution (FORESTER®). An attack on a treated seedling translates into the death of the pathogen but the infested tree dies as well. The treatment plays on the amount of damages (self-insurance) but not on the probability of attack (which still equals 1). Overall, the treatment reduces damages to 25-30% compared to the previous 50-80% without treatment.

The second possible preventive action consists in leaving the soil fallow for two years after the final harvest. In this case, the probability of attack on the stand is halved, which consequently reduces the overall damage with an observed mortality of 5% + 5% of distorted trees. Overall, the fallow reduces the probability of attack to 0.5 (compared to 1 without treatment) and the mortality rate is reduced to 10% (compared to 50-80% without treatment).

3.1.1 Without treatment

The mortality rate associated to an attack of *Hylobius abietis* is uncertain and ranges between 50 and 80%. To deal with this uncertainty, we assume three different values for the potential damages: 50%, 65% and 80%. We also assume the damages occur before the second operations on the stand, *i.e.* before year 2, as indicated in Table 2.

Table 2: Net benefits of a monoculture of Maritime pine with damages of 50%, 65% or 80% due to *Hylobius abietis*

	Damage of 50%		Damage of 65%		Damage of 80%	
Year	Net benef.	Density	Net benef.	Density	Net benef.	Density
0	-900	1000	-900	1000	-9000	1000
2	-70	500	-70	350	-70	200
12	-70	500	-70	350	-70	200
22	684	321	52	321	-70	200
35	7228	0	7228	0	4506	0
NPV^*	$NPV_{H50} = 697.21$		$NPV_{H65} = 400.95$		$NPV_{H80} = -481.54$	

*The NPV is computed considering the additionnal management costs of 39€/ha/yr.

As shown on Table 2, between year 0 and year 2, the higher the percentage of damages, the higher the rate of mortality and the lower the tree density. For a mortality rate of 50% (resp. 65%; 80%), the tree density decreases from 1000 to 500 (resp. 350; 200). Yet one of the objective of the forest owner is to conserve the density values of the benchmark, *i.e.* 500 trees/ha after the first thinning and 321 after the second one. This density is respected with a 50% tree mortality rate, partially respected with a 65% mortality rate (after second thinning) and not respected with a 80% tree mortality rate.

We then compute the LEV for each mortality rate, respectively 50%, 65% and 80% :

$$LEV_{H50} = NPV_{H50} + \left(\frac{NPV_{H50}}{(1+0.015)^{35}} \times \frac{(1+0.015)^{35}}{(1+0.015)^{35}-1} \right) = 995.98e/ha \tag{4}$$

$$LEV_{H65} = NPV_{H65} + \left(\frac{NPV_{H65}}{(1+0.015)^{35}} \times \frac{(1+0.015)^{35}}{(1+0.015)^{35}-1} \right) = 572.77e/ha \tag{5}$$

$$LEV_{H80} = NPV_{H80} + \left(\frac{NPV_{H80}}{(1+0.015)^{35}} \times \frac{(1+0.015)^{35}}{(1+0.015)^{35}-1} \right) = -687.89e/ha \tag{6}$$

As expected, the higher the potential damages, the lower the LEV. However, it appears that the LEV does not linearly decrease with the increase of the damages. As the damages increase from 50% to 65%, the LEV decreases by about 42% while if damages increase from 65% to 80%, the LEV decreases by about 220%. Moreover, the LEV for potential damages of 80% is negative, showing that keeping the trees standing is not an economically consistent option in this case.

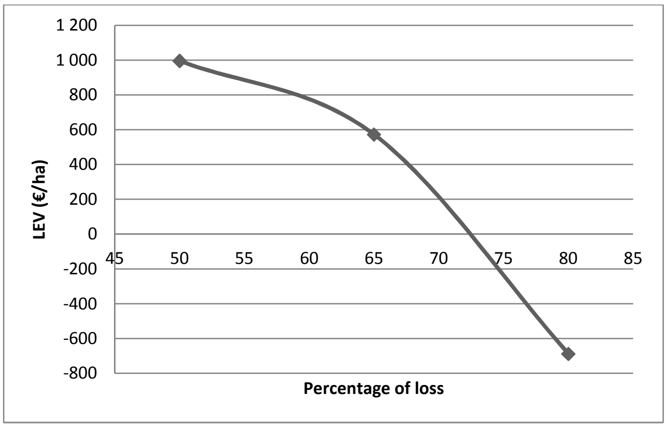

Figure 1: The Land Expectation Value function of the percentage of loss

Figure 1 shows a two-stage curve with almost no impact of the pathogen in the first phase (mortality rate between 50% and 65%). This is because the model assumes the loss due to pathogen is compensated by lower thinning intensities (years 12 and 22), without modifying the density after thinning operations. Since some of the thinned trees are damaged, their unit price is lower, which results in a decrease of LEV value. Conversely, the pathogen appears to significantly reduces LEV value for a mortality rate greater than 65%. In this second phase, the damages due to the pathogen have a direct effect on the density. Consequently, the number of trees standing just before final harvest is lower compared to the benchmark. The decrease in the LEV values results both from the reduction in density and from the decrease of unit prices due to damages on tress, explaining the higher reduction of LEV compare to the two previous situations (damages of 50% and 65%). We can notice here the LEV equals zero for a percentage of loss around 72%.

3.1.2 Self-insurance: FORESTER solution

In this scenario, the seedlings are treated. The treatment costs 0.3 € per seedling, which result in a total plantation cost of 0.17€ (compared to 0.14€ without treatment). Then, the treatment costs 30€/ha. Note that this treatment makes it possible to reduce the damages from 50-80% to 25-30%, as indicated in Table 3.

Table 3: Net benefits of a monoculture of Maritime pine with damage of 25% or 30% due to *Hylobius abietis* under self-insurance

	Damage of 25%		Damage of 30%	
Year	Net benef.	Density	Net benef.	Density
0	-930	1000	-930	1000
2	-70	750	-70	700
12	20	500	2	500
22	684	321	684	321
35	7228	0	7228	0
NPV^*	$NPV_{H25} = 727.03$		$NPV_{H30} = 715.07$	

*The NPV is computed considering the additionnal management costs of 39€/ha/yr.

The self-insurance allows to reduce the damage to 25% (resulting in a density of 750 trees/ha at year 2) or 30% (resulting in a density of 700 trees/ha at year 2). The densities of the benchmark are respected after the first and the second thinnings, but as the pre-thinning density is lower, the net benefit at year 12 is lower compared to the benchmark (20€/ha when the damage is 25% and 2€/ha when it is 30%, respectively, to be compared to the 111€/ha of the benchmark).

We compute the LEV of this scenario for the two percentages of loss, respectively 25% and 30% :

$$LEV_{H25} = NPV_{H25} + \left(\frac{NPV_{H25}}{(1+0.015)^{35}} \times \frac{(1+0.015)^{35}}{(1+0.015)^{35}-1} \right) = 1038.59e/ha \tag{7}$$

$$LEV_{H30} = NPV_{H30} + \left(\frac{NPV_{H30}}{(1+0.015)^{35}} \times \frac{(1+0.015)^{35}}{(1+0.015)^{35}-1} \right) = 1021.49e/ha \tag{8}$$

The difference between the two LEV is really small, around 1% while the damage increases by 5%.

3.1.3 Self-protection: the fallow strategy

We now assume a 2-years fallow period occurs just before the beginning of the rotation to maximise the impact of fallow on the discounted final benefit. Consequently, the rotation goes from year 2 to 37 (compared to year 0 to 35 in the benchmark). The fallow makes it possible to drop the probability of attack from 1 to 0.5. Moreover, the mortality rate decreases from 50-80% to 10%.

Table 4: Net benefits of a monoculture of Maritime pine with and without damage due to *Hylobius abietis* under self-protection

	Damage of 10%		No damage	
Year	Net benef.	Density	Net benef.	Density
2	-900	1000	-900	1000
4	-70	900	-70	1000
14	75	500	111	500
24	684	321	684	321
37	7228	0	7228	0
NPV^*	$NPV_{H10} = 663.53$		$NPV_{H0} = 685.87$	

*The NPV is computed considering the additionnal management costs of 39€/ha/yr.

If the pathogen attacks in the fallow scenario, the damage matches 10% (resulting in a density of 900 trees/ha at year 4). If the pathogen does not attack, all operations are simply postponed by two years compared to benchmark.

We compute the LEV with fallow, both in the case of an attack (*i.e.* damage of 10%) and in the case of no attack (no damage) :

$$LEV_{H10} = NPV_{H10} + \left(\frac{NPV_{H10}}{(1+0.015)^{35}} \times \frac{(1+0.015)^{35}}{(1+0.015)^{35}-1} \right) = 963.82e/ha \quad (9)$$

$$LEV_{H0} = NPV_{H0} + \left(\frac{NPV_{H0}}{(1+0.015)^{35}} \times \frac{(1+0.015)^{35}}{(1+0.015)^{35}-1} \right) = 979.78e/ha \quad (10)$$

The difference between these two LEVs is small (1.5%). This is because trees damaged by the pathogen are young and therefore have a low commercial value. Indeed, the net benefit of the first thinning is 75€/ha in the case of an attack compared to 111€/ha in the case of no attack.

3.1.4 Discussion

Our results are summarized in Table 5:

Our results clearly show that the best economic option for the forest owner is to adopt the self-insurance practice consisting in cypermethrin solution. This treatment minimizes the economic

Table 5: *Hylobius abietis*, synthesis of the LEV (€/ha)

	Without treatment			Self-insurance		Self-protection	
Damage	50%	65%	80%	25%	30%	10%	0%
Prob. attack	100%	100%	100%	100%	100%	50%	50%
LEV	995.98	572.77	-687.89	1038.59	1021.49	963.82	979.78

losses compared to the "best situation", *i.e.* the benchmark. The second best option seems to be the absence of treatment when the damage is 50%. In such a case, the LEV equals 995.98€/ha, i.e. an economic loss of 170.93€/ha. The third option prevailing is the fallow, respectively with damage of 25% and 30%. Finally, the worst option appeared to be the absence of treatment whith damage of 65% and 80%. Notice that with a damage of 80% the LEV is negative and keeping the forest standing is no longer economically relevant. To conclude, the prevention, either self-insurance or self-protection, appears to economically dominate the absence of prevention.

3.2 *Dothistroma septospora and Dothistroma pini*

Dothistroma septospora and Dothistroma pini are two fungis which develop on the spines of pine, further causing their fall. This pathogen do not generate mortality but defoliation, which diminishes the radial growth rate through a quasi-linear relationship. Indeed, a defoliation of 50% decreases the radial growth rate by 50%, and a defoliation of 75% decreases the radial growth rate by 80%. We therefore assume a proportionality between defoliation and radial growth rate.

This pathogen may attack each year but the probability of attack is not known, (*i.e.* uncertainty on the probability of occurrence). To deal with this uncertainty, we assume four different probabilities of attack: 20%, 40%, 60% and 80%.

One preventive treatment against this pathogen consists in a mancozeb solution (DITHANE Paysage®). This is a self-protection activity as it plays on the probability of attack, making it nil. The consequence is that the potential damage also equals zero when the treatment is used (treatment perfectly efficient). However, it costs 14€/kg and two kg/ha are necessary two times per year which results in a costs of 56€/ha/an for this treatment[1].

3.2.1 Without treatment

As previously mentionned, we assume four different probabilities of attack: 20%, 40%, 60% and 80%. The probability of attack applies each year on the stand and is assumed constant over time. We also assume three different potential levels of defoliation: 25%, 50% and 75%. The following Table 6 presents the net benefits for a defoliation of 25% for the different levels of damage.

Table 6: Net benefits of a monoculture of Maritime pine with defoliation of 25% due to *Hylobius abietis*

	Prob. attack 20%		Prob. attack 40%		Prob. attack 60%		Prob. attack 80%	
Year	Net benef.	Density	Net benef.	Density	Net benef.	Density	Net benef.	Density
0	-900	1000	-900	1000	-900	1000	-900	1000
2	-70	1000	-70	1000	-70	1000	-70	1000
12	110	500	109	500	108	500	108	500
22	624	321	567	321	510	321	456	321
35	6909	0	6600	0	6302	0	6012	0
NPV^*	$NPV_{D_{2520}} = 692.62$		$NPV_{D_{2540}} = 572.67$		$NPV_{D_{2560}} = 456.17$		$NPV_{D_{2580}} = 343.15$	

*The NPV is computed considering the additionnal management costs of 39€/ha/yr.

The *Dothistroma septospora and Dothistroma pini* infection do not modify the density but generate a reduction in the radial growth rate. Without defoliation and without damage, the circumference of the tree grows from 50 cm at year 11 to 54 cm at year 12 while with a defoliation rate of 25% and a probability of attack of 20%, the circumference grows from 50 cm at year 11 to 53.53 cm at year 12 (from 50 cm to 53.34 cm with a probability of 40%, from 50 cm to 53.16 cm with a probability of 60% and from 50 cm to 52.97 cm with a probability of 80%).

We compute the LEV as a function of the probability of attack and of the defoliation rate. For instance, the LEV for a defoliation of 25% and a probability of damage of 20% is calculated as follows:

$$LEV_{D_{2520}} = NPV_{D_{2520}} + \left(\frac{NPV_{D_{2520}}}{(1+0.015)^{35}} \times \frac{(1+0.015)^{35}}{(1+0.015)^{35}-1} \right) = 989.43e/ha \qquad (11)$$

The results presented in Table 6 stand for a defoliation rate of 25% but the same reasoning applies for rates of 50% and 75%. The entire results are summarized in the following Table 7.

Table 7: The LEV (€/ha) for *Dothistroma septospora and Dothistroma pini* without treatment for a defoliation rate of 25%, 50% and 75% respectively

Damage (defoliation)	25%			
Prob. attack	20%	40%	60%	80%
LEV	989.43	818.07	651.65	490.19

Damage (defoliation)	50%			
Prob. attack	20%	40%	60%	80%
LEV	818.07	490.19	182.11	-106.19

These results clearly show that the higher the probability of attack or the defoliation rate, the lower the expected LEV. The graph therefore provides an illustration of what would happen in

Damage (defoliation)	75%			
Prob. attack	20%	40%	60%	80%
LEV	651.65	182.11	-242.91	-623.4

terms of LEV if the frequency of the risk increases and/or the intensity of the damage increases, for instance because of climate changes.

3.2.2 Self-protection: mancozeb solution

The additional treatement cost of 56€/ha/an is now included in the sylvicultural model. As a result, the probability of attack equals zero and the damage is nil. The NPV equals now $NPV_{D_{00}} = -359.17$ €/ha and the LEV :

$$LEV_{D_{00}} = NPV_{D_{00}} + \left(\frac{NPV_{D_{00}}}{(1+0.015)^{35}} \times \frac{(1+0.015)^{35}}{(1+0.015)^{35}-1} \right) = -513.09e/ha \tag{12}$$

The treatment reduces the LEV of the private forest owner from 1166.91 €/ha in the benchmark to -513.09 €/ha here. This clearly means that the forest owner has no economic interest to adopt such a treatment, even if perfectly efficient. One question is arising as to which treatment cost is compatible with a positive LEV in this case, we find a value of 38.85€/ha/an, i.e. 45% lower than the current one.

3.2.3 Discussion

Figure 2 presents the synthesis of the results with and without treatment.

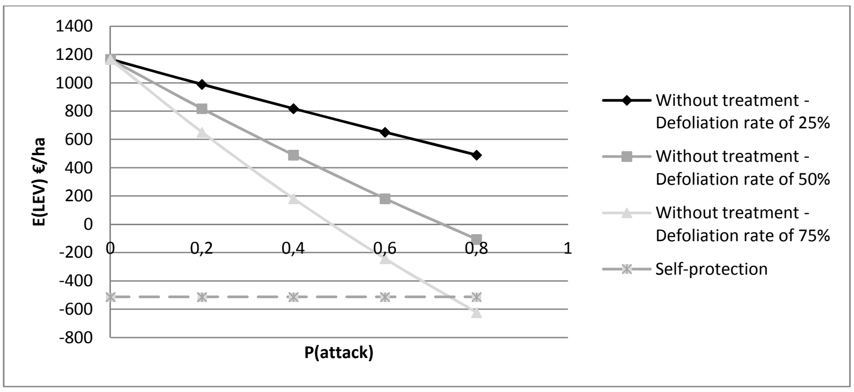

Figure 2: *Dothistroma septospora and Dothistroma pini*, synthesis of the results

It appears that the prevention in terms of self-protection is never interesting for the forest owner since it leads to economic losses. The LEV with treatment economically dominates only one situation which is the more catastrophic one, *i.e.* probability of attack of 80% and defoliation rate of 75%.

3.3 *Heterobasibion annosum*

Heterobasibion annosum is a basidiomycetous fungi which causes roots rot (Asiegbu et al. [2]). Following Stenlid et al. [52] it is considered to be the most economically important forest pathogen in the Northern Hemisphere. In Europe alone, *Heterobasibion annosum* is responsible for the loss of 800 million euros annually (1billion dollars US), and this pathogen is also widespread in forests in the USA.

Assessments of economic losses due to *Heterobasibion annosum* are generally obtained through the measurement of the reduction in yield and value of timber. Following Gonthier et al. [19] such estimates have been performed in plantations of Sitka spruce (*Picea sitchensis (Bong.) Carr.*) (Pratt [41]), Norway spruce (Fedorov and Poleshchuk [18]) and Scots pine (*Pinus sylvestris L.*), but not on Maritime pine. Invasion occurs through wind dissemination of spores, which are able to infect stumps during 1 month after harvest (Lung-Escarmant [36]).

We distinguish two different types of self-protection strategy. The first one consists in a preventive treatment on healthy plots which objective is to keep the probability of attack equals to zero. This preventive treatment (Polybor®and Rotstop®) is 100% effective (Soutrenon et al. [51]) when used before any contamination. It must be applied just after harvesting on recently harvested stumps. The second type of self-protection strategy is a curative treatment on infected plots which objective is to stop or slow down dissemation. In this case three strategies exist: local stumps removal, total stumps removal or a fallow at the end of rotation.

Our result presented hereafter assume that (1) contamination may happen during the clearing (year 2), the first thinning (year 12) or the second thinning (year 22); (2) when a contamination happens there are 12 contamination centers per hectare and the speed of contamination from the heart of the contamination center equals 0.3 m/year.

3.3.1 Without treatment

As indicated above, the contamination may occur at year 2, 12 or 22. Then, regarding the period of contamination, the net benefits differ from each other, as indicated in Table 8. Note that density remains the same whatever the scenario, however the commercial value of contaminated trees is 0.

Table 8: Net benefits of a monoculture of Maritime pine when contamination with *Hylobius abietis* occurs at year 2, 12 and 22 respectively

	Contamination yr 2		Contamination yr 12		Contamination yr 22	
Year	Net benef.	Density	Net benef.	Density	Net benef.	Density
0	-900	1000	-900	1000	-900	1000
2	-70	1000	-70	1000	-70	1000
12	26	500	33	500	33	500
22	503	321	580	321	606	321
35	4453	0	5840	0	6731	0
NPV^*	$NPV_{HA2} = -44.07$		$NPV_{HA12} = 411.94$		$NPV_{HA22} = 691.33$	

*The NPV is computed considering the additionnal management costs of 39€/ha/yr.

We compute the LEV function of the period of contamination, year 2, 12 or 22 as follows:

$$LEV_{HA_2} = NPV_{HA2} + \left(\frac{NPV_{HA2}}{(1+0.015)^{35}} \times \frac{(1+0.015)^{35}}{(1+0.015)^{35}-1} \right) = -62.95e/ha \tag{13}$$

$$LEV_{HA_{12}} = NPV_{HA12} + \left(\frac{NPV_{HA12}}{(1+0.015)^{35}} \times \frac{(1+0.015)^{35}}{(1+0.015)^{35}-1} \right) = 588.46e/ha \tag{14}$$

$$LEV_{HA_{22}} = NPV_{HA22} + \left(\frac{NPV_{HA22}}{(1+0.015)^{35}} \times \frac{(1+0.015)^{35}}{(1+0.015)^{35}-1} \right) = 987.58e/ha \tag{15}$$

As expected, the earlier the contamination, the lower the LEV since more trees are contaminated as the pathogen spreads over time at a 0.3 m/year speed. The LEV is even negative if contamination occurs at the very beginning of the rotation, making the conservation of the stand economically irrelevant.

3.3.2 Preventive treatment as self-protection

We assume the preventive treatment on healthy plots costs 1€$/m^3$ of wood removed from the forest. With this preventive treatment the probability of attack is nil and so is the the damage. Values of Table 1 are modified to include the cost of the preventive treatment, the NPV associated is: $NPV_{HA} = 594.14e/ha$.

We compute the LEV associated to this preventive treatment as follows:

$$LEV_{HA} = NPV_{HA} + \left(\frac{NPV_{HA}}{(1+0.015)^{35}} \times \frac{(1+0.015)^{35}}{(1+0.015)^{35}-1} \right) = 848.74e/ha \tag{16}$$

The treatment reduces the LEV by 27% compared to the benchmark but guarantees the absence of contamination. Compared to previous figures, it appears that preventive treatment is always economically-relevant except when contamination occurs lately in the stand (during the last thinning).

3.3.3 Curative treatments: local stumps removal, total stumps removal and fallow as self-insurance

We here assume that the stand is already contaminated (contamination certain). We assume the stump removal costs 690 €/ha. In the case stumps are locally removed, only stumps on the contaminated area are removed. The contaminated area depends on the age of contamination: the earlier the contamination, the bigger the contamination area. In the fallow scenario, we consider a 5-years fallow at the end of the rotation.

Table 9: *Heterobasibion annosum*, LEV (€/ha) function of the period of contamination and of the curative treatment

	Local stumps removal	Total stumps removal	5-years fallow
Contamination year 2	983.98	-358.63	459.78
Contamination year 12	998.80	292.78	785.48
Contamination year 22	939.27	691.9	985.04

Three main conclusions can be drawn from these value and their comparison with the LEV for the preventive treatment. First, our results show that, whenever the date of contamination, a local stump removal is always more profitable than a systematic preventive treatment. Second, whenever the date of contamination, the total stump removal strategy always appear to be the least economically profitable strategy regarding other srategies. Moreover, it is the only strategy which result in a negative LEV in the case where contamination occurs at age 2. Finally, the choice between a local stump removal and a fallow depends on the date of contamination: if the contamination occurs at year 2 or 12, the local stump removal result in a higner LEV than the fallow. Otherwise, if the contamination occurs at year 22, the fallow must be favored.

4 Discussion

4.1 The choice of a discount rate

Several possibilities exist to determine the discount rate (Chevalier et al., [11]). First, one can adopt the rate fixed by the Commissariat Général du Plan [16] for public project (4% during 30 years and decreasing after from 4% to 2%). Second, one can determine discount rate in relation with preference for the present, the time horizon concerned and the level of uncertainty. In the forestry sector, it is usual toconsider discount rate between 1% and 4%. Third, it is possible to deduce discount rate from the characteristics of the stand. Indeed, the stand is described in terms of costs and benefits, allowing to determine the LEV via a discount rate. Then, either we know the discount rate and we calculate the LEV or we know approximately the LEV and we compute the discount rate. In this paper, we adopt this last methodology. Indeed, among the forestry experts, the LEV for a stand of Maritime pine with rotation lenght of around 35 years should be around 1200€/ha. Then, given our costs and benefits data, in order to obtain such a LEV, the discount rate should be equal to 3.5%. Thus, we assume a discount rate of 3.5% in our study corresponding to a LEV in the benchmark of 1166.91€/ha. The choice of this discount rate is consolidate by forest economics literature which stipulate usual discount rates for forest project between 2% and 4% (Brukas et al. [8]).

Nevertheless, we conduct a sensitivity analysis on this parameter to ensure the robustness of our results. We test for discount rate of 3% and 4%. We show that the trends are the same whatever the pathogenic risks considered and with or without treatment. With a discount rate of 3% the LEV of the benchmark is 1860.28 €/ha and with 4% it is 665.26 €/ha, values that are really far from the 1200€/ha suggested by the forestry experts.

4.2 Adaptation to climate change

In plantation forests, several adaptation strategies exist, involving the change of species and/or clones more adapted to new conditions, the preference for mixed-species stands, additional management operations (such as fallows or stump removals) or conventional treatments. Compared to other strategies, these conventional treatments appear as rather conservative as they do not imply any changes in forest management choices. Three of the prevention options considered in our paper belong to this category: cypermethrin solution for *Hylobius abietis*, mancozeb solution for *Dothistroma septospora and Dothistroma pini* and Polybor®and Rotstop®for *Heterobasibion annosum*. Although cypermethrin solution better performs than other strategies for the prevention of *Hylobius abietis*, one may question the long term implications of this strategy in a context of climate change. In fact, this option allows to conserve production activity on the short-term while maintaining (or even increasing) exposure and vulnerability of Maritime pine monoculture in the long term. Following Noble et al. ([39]), this strategy can therefore be considered as maladaptation as it delivers short-term economic gains but leads to greater vulnerability in the medium to long-term.

Conversely it has been shown that risk spreading by promoting mixed-species stands, whose resilience to forest pathogens is higher than monocultures, combined with natural regeneration

(Kramer et al.[33]), is a relevant adaptation strategy for temperate forests (Hemery [21], Bolte et al.[7]). Species and provenances must be chosen taking into account future potential climatic space which is likely to shift from several km to several tens of km per decade, most probably faster than natural migration.

Other strategies studied in our paper (stump removal and fallow) stay in-between, allowing for more flexibility in management practices but maintaining the mono-species type of management.

5 Conclusion

This paper proposed to analyse the economic relevance of several prevention strategies for three major forest pathogens in Landes forest: *Hylobius abietis*, *Heterobasibion annosum* and *Dothistroma septospora*. To do so, we used a cost-benefit framework and determined the Land Expectation Value associated to scenarios with and without prevention strategies and compared them to a benchmark scenario without pathogen risk. Three main results stem from our analysis.

First, the comparison of the LEV in the benchmark with the LEV in the scenarios with pathogen without treatment show that the economic impact of pathogen is highly uncertain and depends on the type of pathogen, the level of contamination or the age of contamination. In addition, our result show that all pathogens studied can potentially lead to a negative LEV, therefore implying a pure loss for forest owner. This stresses the need for relevant prevention strategies.

Second, we showed that conventional treatments (cypermethrin, mancozeb, Polybor®and Rotstop®) do not always better perform compared to the absence of treatment or alternative treatments. In particular, we showed that (1) using a mancozeb solution to fight against *Dothistroma septospora* is almost never economic relevant and (2) local stumps removal is more profitable than Polybor®and Rotstop®solutions to fight against *Heterobasibion annosum*. Nevertheless, the cypermethrin solution remain the more economic relevant option to prevent *Hylobius abietis*.

Third, it appears that one important driver of economic loss is the impact of the pathogen on the final stand density. Indeed, we showed that *Hylobius abietis* do not only reduce economic gains by reducing the economic value of contaminated tree, but also by reducing the overall density which result in a non-linear LEV decrease over time.

Overall, we think our work would substantially benefit from several extensions.

First our methodological framework could be modified to include a cost-benefit analysis under uncertainty approach making it possible to take risk aversion into account through (either non-linear or not) welfare functions or the explicit introduction of a risk premium. Besides, a real option technique could make it possible to represent the possibility of delaying a decision until more information is available, which is of great value regarding adpatation strategies.

Second, as presented in the discussion, we deeply believe there is an increasing need for more resilient-based adapatation strategies within plantation forests. In this view, one could question the impacts of the introduction of mixed-species stands or genetic selected clones. In this case, the cost analysis would require to account for the modification of harvest methods, machines and processes as well as potential need in research and development areas.

Third, forest ecosystem services such as carbon sequestration or its role as a biodiversity sanctuary are also impacted by pathogens invasion. This has to be considered in a comprehensive analysis of the economic impacts of pathogens over forest stands.

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