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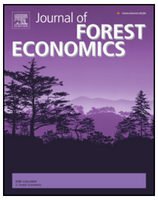

Land expectation value and optimal rotation age of maritime pine plantations under multiple risks

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ABSTRACT

Maritime pine (*Pinus pinaster*) is the most important conifer species in France in terms of wood production. It is mostly cultivated in even-aged monoculture stands in the Landes forest. These plantations are exposed to multiple biotic and abiotic risks: most importantly the cyclical outbreaks of a defoliator, the Pine Processionary Moth (PPM, *Thaumetopoea pityocampa*), and storms causing large windthrown. This study aims to compute the optimal rotation age and land expectation value (LEV) for maritime pine plantations in order to assess the impact of these disturbances. Using stochastic simulation methods, we simulate multiple scenarios combining different disturbance intensities. Our results show that both disturbances reduce LEV individually. When combined together, the two disturbances generate subadditive losses (i.e. combined damages are smaller than the sum of the damages from each disturbance individually). The impact on the optimal rotation length, however, is different for the two analysed risks: While storms tend to reduce the optimal harvest age, PPM tends to increase it. Overall, the impact of PPM on the rotation length prevails and, here, risks increase rather than decrease the optimal rotation length. Thinnings play an important role. They do not only increase profitability but also constitute an effective hedging strategy against both risks since they mitigate the negative impacts of PPM and storm disturbances for all the tested scenarios.

Introduction

Maritime pine (*Pinus pinaster*) is the most important conifer in France in terms of wood production (6.4 million m^3 $year^{-1}$). It is grown mostly in south-western France, in the Landes forest area, as a pure even-aged monoculture, mostly on private land. These plantations are subject to different kinds of risks. On the one hand, biotic risks related to pathogens and pests and, on the other hand, abiotic risks such as storms and, to a lesser extent, fires.

As far as the biotic risks are concerned, the main pest affecting maritime pine is the Pine Processionary Moth (*Thaumetopoea pityocampa*). Pine Processionary Moth (henceforth denoted PPM) is the most important defoliator in southern Europe. PPM outbreaks follow a cyclical pattern with a periodicity of about 7 years (Li et al., 2015). These outbreaks may lead to large losses in pines' annual growth but do not cause trees' death. It has been estimated that during an outbreak the radial growth loss can reach 93% (Jacquet et al., 2013). In the past, PPM population was controlled by aerial spraying of insecticides, but nowadays EU regulations and increasing costs are strongly limiting the use of these practices in forests.

Among abiotic risks, wind storms are a huge concern for forest managers in the region. In 1999, storm Martin felled about 23 million cubic metres of maritime pine, representing about 19% of the standing stock (IFN, 2003). Ten years later another heavy storm event hit the Landes region: Storm Klaus felled about 37 million cubic metres of maritime pine in south-western France, corresponding to 29% of the maritime pine growing stock and total monetary losses estimated in the range of EUR 1.34 and EUR 1.77 billion (IFN, 2009; Costa et al., 2009).

These natural disturbances alter forest development and pose serious challenges to forest management. Furthermore, given climate change the frequency and intensity of these shocks may change. Is it possible to quantify the expected losses? How should management practices change in order to reduce the negative impacts of these disturbances? Responding to these two questions requires a high degree of integration of ecological and economic models. The main objective of this paper is to determine the impacts

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of PPM outbreaks and storms on forest management. In particular, we want to determine the optimal rotation age and the land expectation value (LEV) under different scenarios of PPM outbreaks intensity and storm frequency and intensity. We firstly analyse the problem without considering thinnings and then introduce them exogenously, following commonly used thinning schemes in the region.

In this paper, we integrate the traditional Faustmann (1849) model for even-aged forest plantations with the ecological dynamics of PPM and the impacts of storms. The impacts of catastrophic events and the risk of total destruction on the optimal rotation age have been addressed by previous works (Martell, 1980; Routledge, 1980; Reed, 1984). In these earlier works the catastrophic event is treated as exogenous and assumed to cause full destruction of the stand. Successively, Haight et al. (1995) introduced age-dependent damage risk and salvage proportion. Thorsen and Helles (1998) investigated the optimal rotation length and optimal thinning regime using an endogenous damage function. Both Haight et al. (1995) and Thorsen and Helles (1998) assumed an exogenous land value. Loisel (2011, 2014) computed the optimal rotation age and thinning regime under the risk of destructive events considering the value of successive rotations endogenously – as in Faustmann (1849) – while accounting for the salvage value of windthrown timber. In all these studies, the forest stand was completely cleared after a storm event, independently of the level of damage. Recently, Petucco et al. (2017) showed that it might be profitable not to harvest the standing trees after a storm. In this paper we follow this last approach, i.e. the stand is clear cut after a storm if and only if it is more profitable to do so than letting the remaining standing trees grow until maturity. We add to the work of Petucco et al. (2017) a second disturbance (a defoliator pest) in order to analyse forest management in a multiple-disturbance context.

Different approaches have been used for the economic analysis of the impacts of pest disturbances on forest management. Pest disturbances were initially integrated in a Faustmann setting as an age-dependent exogenous risk of destruction assuming total clearing and replanting after the infection of the stand (Reed and Errico, 1987). Successively, age-dependent survival probability and Monte Carlo simulations were used to assess the risk of total destruction by pathogens, pests and storms and their impacts on the land expectation value (Dieter, 2001; Staupendahl and Möhring, 2011; Griess and Knoke, 2013). Recently, Macpherson et al. (2016) coupled a single-rotation Faustmann model with an epidemiological model and computed the optimal rotation age for different spread rates and levels of damages. Specifically addressing the impacts of PPM, Gatto et al. (2009) quantified the total costs of PPM outbreaks assuming an exogenous rotation age and exogenous and constant timber growth loss.

Few studies have addressed multiple disturbances simultaneously: Reed and Errico (1987) investigated the impacts of fire and pest disturbances on the land expectation value and Valsta (1992) analysed the optimal rotation age and the optimal thinning problems accounting for randomly yearly growth rate levels and catastrophic events. Two recent works by Xu et al. (2016a,b) addressed the optimal rotation age problem when facing two catastrophic disturbances, generalising the approach used by Reed and Errico.

Compared to previous works, firstly, we considered two different types of forest disturbances: a catastrophic disturbance – i.e. windstorms – and a growth-reducing disturbance – i.e. PPM outbreaks. We explicitly model the PPM dynamics and, then, link it with the annual growth rate reduction by coupling an economic and ecological model. None of the previous studies modelled the pest damages as a direct function of the pest population dynamics. Secondly, we combine the impacts of multiple risks (PPM and storms) using endogenous damage functions that depend on the state of the forest.

In the next section we present the theoretical model starting from the benchmark model without risk. Then we present the PPM-outbreak module and storm models. The third section presents the numerical method used to solve the model and the fourth section illustrates and discusses the results of the simulations. Finally, in the fifth section, we present our conclusions.

The model

The model is based on Faustmann (1849) work, where the forest owner maximises the land expectation value (LEV) over an infinite horizon. The forest owner's control variable is the rotation length R. Specifically, LEV represents the infinite sum of discounted net returns from a forest plantation which – in a deterministic setting – can be written as follows:

$$\max_{R} \sum_{t=0}^{\infty} \frac{\pi(a(t)) - C_P(a(t))}{(1+r)^t}, \tag{1}$$

where r is the discount rate, $a(t)$ is the age of the standing trees at each time period t, C_P is the planting cost, which is different from zero when $a(t) = 0$ and null elsewhere, and $\pi(a(t))$ represents the net timber revenues. The age of the stand determines the implementation of the different management operations. The model is discrete in time, with one-year increments. Consequently, the age of the standing trees $a(t)$ increases one year at each time step and is set to zero after a final felling, every R years. The stumpage value is defined as:

$$\pi(t) = P(d(t))\, q(t) - C_V\, q(t) - C_F, \tag{2}$$

where $P(\cdot)$ is the timber price which is a continuous monotone increasing function of the stand's average tree diameter $d(t)$; C_V represents the variable harvesting and extraction costs expressed in volume units and C_F the fixed harvesting and extraction costs. The volume harvested is denoted by $q(t)$. In our paper, we consider two types of harvesting: a final cut and several periodical thinnings. The final cut sets end to the rotation by harvesting the total standing volume $V(t)$ and leads to a new planting cycle. In contrast, thinnings remove only a part, $E(t, A_i)$, of the total standing volume, with subscript i indicating the sequential number of thinning interventions which are performed at pre-specified times, A_i. In total, $\bar{E} \geq 0$ thinnings are performed. The amount of volume removed at each thinning, the corresponding number of trees removed, $K(t)$, as well as the thinning ages are all exogenous and may differ from one thinning to another according to the best silvicultural practices available.[1] The volume harvested can then be summarised as:

$$q(t) = \begin{cases} V(t), & \text{if} \quad a(t) = R, \\ E(t, A_i), & \text{if} \quad a(t) = A_i, \quad i = 1, \ldots, \bar{E} \quad \text{with} \quad E(t, A_i) < V(t), \\ 0 & \text{elsewhere} \end{cases}$$

In the rest of this section, we add to this deterministic model two types of stochastic disturbances: a growth-reducing disturbance (i.e. the defoliator pest) and a catastrophic disturbance (i.e. windstorms). Following existing evidence, we assume that the occurrence of each disturbance is independent from the other and exogenous. That is, storms and pest outbreaks arrive over

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[1] Note that the timing of the thinning is not a decision variable in the model. We rather account for the fact that best current silvicultural practices in the Landes Region typically include five thinnings at age 13, 19, 26, 33, 39. These thinnings improve the growth and quality of the stand, thus leading to greater future revenues.