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Multiple-stand forest management under fire risk: Analytical characterization of stationary rotation ages and optimal carbon sequestration policy☆

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ABSTRACT

This paper focuses on the characterization of stationary states for a multiple-stand forest that is subject to forest fires and managed by a producer who has expected utility preferences. An analytical and tractable characterization of the stationary rotation age is established on the basis of Karush–Kuhn–Tucker conditions. The rotation age is shown to be unique and to depend on the risk probability but not on producer's risk preferences. A numerical application, using these analytical findings and based on the forestry of maritime pine in southwestern France is conducted. This numerical application consists in designing an optimal carbon sequestration policy based on financial incentives aiming at extending forest rotation ages. Results show that forest fire probability has a significant decreasing impact on sequestration costs.

Introduction

Fire is a major risk in forestry and its importance in Europe is expected to grow in the future as a result of climate change (Schelhaas et al., 2010). Perturbation risks, such as fires, have a direct impact on forest management through the damages they may cause, and an indirect impact through the precautionary behaviors they may induce among producers.

The issue of risk in forest management can be addressed using different types of models. The oldest and most prominent category of forest management models consists of Faustmann's rotation models (Faustmann, 1849). Faustmann's rotation models are aimed to determine the optimal harvest age of a single-stand forest, which rotation repeats forever. Rotation models are often defined in a continuous time setting. In his seminal paper, Reed (1984) studies the impact of the risk of forest fires using a Faustmann's rotation model and an identically and independently distributed Poisson jump process to describe the risk. It shows analytically that the risk of fire reduces the optimal rotation length. Modeling a perturbation risk through a Poisson process or equivalently in a discrete time setting through a sequence of Bernoulli trials has been a standard assumption ever since.

Reed (1984) considers risk-neutral producers. On the contrary, some later studies focus on risk averse producers. For example, Caulfield (1988) proposes a mean-variance approach to represent the producer's risk aversion. He shows that risk aversion tends to shorten rotations but the mean-variance framework is by definition not suited to identify a unique solution. Couture and Reynaud (2011), among others, show in an expected utility framework that risk aversion tends to reduce rotation ages.

Another type of models used to consider forest management under risk consists of two-period models. These models are focused on the analysis of intertemporal trade-offs. Koskela (1989) uses a two-period model and shows that risk aversion increases the present consumption at the expense of the future one, which reveals a precautionary behavior. Single-stand rotation models and two-period models are adapted to deal respectively with optimal rotation ages and intertemporal trade-offs but they do not answer to questions on optimal age-class structures.

The optimal management of a forest with multiple age-classes in a discrete time setting and in a deterministic context is the focus of many studies. Mitra and Wan (1985), and Mitra and Wan (1986) analytically show that in presence of discounting, the optimal rotation age is given by Faustmann's rule and thus does not depend on intertemporal preferences. Moreover, they provide numerical evidence that shows the existence of stationary periodic forests following Faustmann's rule. Later, Salo and Tahvonen (2002a,b), using Karush–Kuhn–Tucker conditions, demonstrate analytically the existence of a continuum of stationary periodic forests around Faustmann's normal forest that all respect Faustmann's rule. However, despite respecting Faustmann's rule, which is independent from preferences, this set of periodic forests depends on preferences as for the stationary forest structures it contains.

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The stationarity of periodic forests is due to the discrete time setting as they tend to disappear when time steps tend to zero. In addition, Salo and Tahvonen (2003) show that there are no stationary periodic forests whenever Faustmann's age is not unique, which only happens as a limit case in a deterministic context.

The issue of multiple-stand forest management in a stochastic context has so far mainly been addressed numerically. For example, Couture and Reynaud (2008) have developed a stochastic dynamic programming model that is used to analyze both the stationary states and transitory dynamics of a forest with multiple age-classes whose owner has recursive preferences. Dumollard and De Cara (2017) have recently completed this approach by considering the possibility to reallocate land to an alternative use (e.g. agriculture).

The aim of the present study is to propose an analytical characterization of the stationary rotation age of an even-aged forest with multiple age-classes, when this forest is subject to forest fires and the producer has expected utility preferences.

Stationary states are optimal to perpetuate as long as no perturbation (here fires) occurs. Focusing on stationary states in presence of a perturbation risk is particularly relevant when the probability of this risk is low as the forest is then more likely to converge and to remain in a stationary state. However, in any case, the stationary state is a horizon to which the producer's decisions tend to lead, and is as such a good indicator of the producer's behavior.

The problem is formally described using a mathematical optimization program presented in detail in Section ‘A stochastic dynamic forest management program’. This optimization program is solved analytically on the basis of Karush–Kuhn–Tucker conditions. The results and their demonstration are presented in Section ‘Analytical characterization of stationary forests under expected utility preferences’.

At last, a numerical application of these results to the forestry of maritime pine in southwestern France is presented in Section ‘A numerical application: maritime pine forestry in southwestern France and optimal carbon sequestration policy’. This numerical application is aimed to illustrate the meaning of analytical results. It consists in designing an optimal carbon sequestration policy based on financial incentives aiming to extend forest rotation ages. In particular, an assessment of the effect of forest fire probability on sequestration costs is carried out.

A stochastic dynamic forest management program

The model considered in this study describes an even-aged forest. In this model, the forest management is flexible and allows for forests with multiple age-classes. As the different age-classes are spatially separated (even-aged forestry), there are no interaction effects between age-classes in terms of growth dynamics. Moreover, there is no thinning in the model: on a given land acreage, timber is either totally harvested or not harvested at all. However, an age-class may be harvested only on a fraction of the total land acreage it covers.

In addition, it is assumed that a fire can randomly occur at any time, destroying completely the forest. A complete destruction means that all the considered forest is left with no economic value and no growth potential, the forest must be replanted. The complete destruction assumption is plausible when considering fire risk on reasonably small forest areas, for example on the level of a single private owner's property. This assumption would however be too strong if we considered a storm risk as storms only partially destroy forests. These assumptions ensure that the state of the forest at a given time can be completely described by the land shares allocated to the different age-classes, noted $x_{a,t}$ with $a \in \mathbb{N}^*$ the age-class index and $t \in \mathbb{N}$ the time index.

The problem faced by the producer is set in discrete time, it is sequential and identical for every period of time. At a given time t, the producer observes the state of his forest, which is defined by the vector of land shares $X_t = (x_{1,t}, x_{2,t}, \ldots, x_{a,t}, \ldots)$. On the basis of this observation, he makes harvest and planting decisions. These decisions

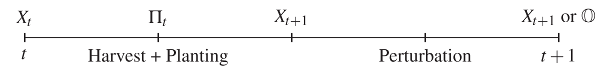

Fig. 1. Timeline of decisions and realizations between t and $t + 1$.

determine income Π_t received at time t, which is certain from a time t perspective. These decisions also determine land shares $X_{t+1} = (x_{1,t+1}, x_{2,t+1}, \ldots, x_{a,t+1}, \ldots)$ that will be realized at time $t + 1$ if no fire occurs between t and $t + 1$ and after age-classes grew older by one period. Once decisions are made and executed, a fire occurs with probability p and does not occur with probability $(1 - p)$. The probability is assumed to be independent from the forest age although in reality, younger forests are more prone to the fire risk. If the fire does not occur, “decided” state $X_{t+1} = (x_{1,t+1}, x_{2,t+1}, \ldots, x_{a,t+1}, \ldots)$ is actually realized at $t + 1$, otherwise state $X_{t+1} = (0, 0, \ldots, 0, \ldots) = \mathbb{O}$ is realized instead.

The elementary sequence of decisions and realizations between t and $t + 1$ is represented in Fig. 1:

Once the state at $t + 1$ is realized, the producer observes it and the same sequence of decisions and realizations reproduces, and so forth indefinitely.

Decisions made between t and $t + 1$ can be fully expressed through land shares X_t, corresponding to the state of the forest observed at t, and “decided” land shares X_{t+1}. Thus, the acreage of age-class a that is harvested between t and $t + 1$ is noted $h_{a,t}$ and can be expressed as follows:

$$\text{For all } a \in \mathbb{N}^* \text{ and } t \in \mathbb{N}\text{: } h_{a,t} = x_{a,t} - x_{a+1,t+1} \tag{1}$$

The acreage planted with new forest between t and $t + 1$ is denoted s_t and can be expressed as follows:

$$\text{For all } t \in \mathbb{N}\text{: } s_t = x_{1,t+1} \tag{2}$$

The producer is assumed to have expected utility preferences. Therefore, his objective function can be written as follows:

$$\max\left\{\mathbb{E}\left[\sum_{t=0}^{+\infty} \beta^t u(\widetilde{\Pi}_t)\right]\right\} = \max\left\{\sum_{t=0}^{+\infty} \beta^t \mathbb{E}[u(\widetilde{\Pi}_t)]\right\} \tag{3}$$

β is the discount factor, $\mathbb{E}$ is the expectancy operator, $\widetilde{\Pi}_t$ is the random income that is realized at time t (uncertain from a time 0 perspective), and u is the utility function describing the producer's preferences.

As the model is given an infinite time horizon and as the fire process is an infinite sequence of independent and identical Bernoulli trials, the sequential problem can be represented on the binomial tree given in Fig. 2:

Starting from an exogenous initial state X_0, the producer decides on vectors of land shares $(X_1, X_2, \ldots)$ that will be realized as long as no fire occurs. He also decides on the land shares that will be realized in all the other fire realization scenarios. However, as the occurrence of fires

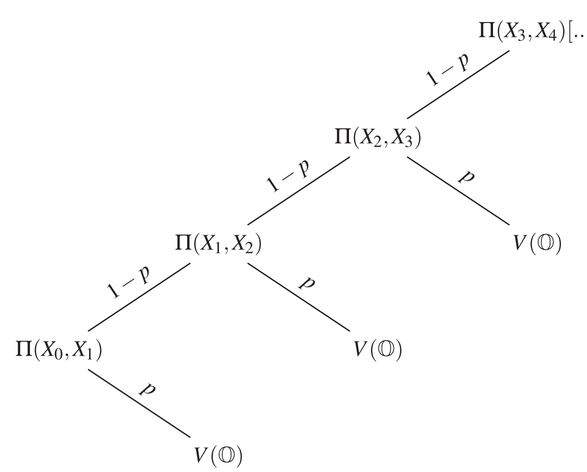

Fig. 2. The stochastic fire binomial tree.