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Forest management with wildfire risk, prescribed burning and diverse carbon policies☆

Zhuo Ning [a], Changyou Sun [b,*]

[a] College of Economics and Management, Nanjing Forestry University, Nanjing, PR China
[b] Department of Forestry, Mississippi State University, Mississippi State, MS 39762, USA

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ABSTRACT

Forests absorb carbon dioxide through photosynthesis and also can release it back into the atmosphere through natural disturbances and management activities. In this study, the impact of different carbon policies on a landowner's management decisions is analyzed at the stand level. Wildfires as a random natural phenomenon and forestry prescribed burning as a fuel treatment tool are all considered within the framework of a generalized Faustmann model. The results reveal that harvesting rotations and land values can be affected by the level and pattern of wildfire risk, and additionally, the consideration of carbon in various policies. In response to different carbon policies, the optimal time of prescribed burning only varies slightly, but its intensity can experience much larger variations. If the landowner needs to pay for carbon emission from prescribed burning but not from a wildfire, the optimal strategy is to conduct the prescribed burning more lightly and later than in the base scenario. Overall, participation in a carbon program results in a higher land expectation value, which is beneficial to the landowner. These research findings are helpful for understanding the relation between carbon policies and the behavior of landowners, and furthermore, for improving carbon policy designs.

1. Introduction

Forests sequester carbon from the atmosphere, so they can be managed to store more carbon if extra benefits are offered to landowners (Binkley et al., 2002). On the contrary, forest management activities, such as site preparation and harvesting, can release carbon back into the atmosphere. Meanwhile, natural disturbances, especially wildfires, occur on forests randomly and release a large amount of carbon as well. Therefore, forests are relevant to the issue of climate change in several ways.

In particular, wildfires are inherent in many ecosystems. From 1985 to 2000, an average of 77 thousand wildfires burned 3.5 million acres of forestland each year in the United States; the corresponding numbers were 73 thousand wildfires and 6.5 million acres from 2001 to 2014 (National Interagency Fire Center, 2015). Thus, the average size of a wildfire has become larger in recent years. Furthermore, wildfires generate about 293 million metric tons of CO_2 each year, equivalent to 4–6% of annual anthropogenic emissions in the United States (Wiedinmyer and Neff, 2007). In contrast, forestry prescribed burning is a common management tool that can be used to improve forest health and reduce damage from catastrophic wildfires, especially for fire resistant species (Knapp et al., 2009). In recent several decades, more than two million acres of forestland were treated with prescribed burning every year in the United States, and a majority of them are commercial forests in the South (Haines et al., 2001). Even though prescribed burning is usually controlled within the predefined boundary, it does generate smoke and release carbon similar to a wildfire.

Wildfire risk has been incorporated into the analyses of various management issues in forestry through different models. Reed (1984) first improved the standard Faustmann model by assuming a Poisson stochastic process for wildfire occurrences. This approach has been followed or expanded to examine the optimal expenditure on wildfire protection (Reed, 1987), non-market values of forests (Englin et al., 2000) and levels and time of fuel treatment activities (Amacher et al., 2005). General stochastic process has also been applied in natural catastrophe studies, in which a landowner's decision becomes a continuous-time optimal stopping problems that can be modeled by Ito's lemma to capture uncertainties in a richer way (Yin and Newman, 1996). Similarly, Stainback and Alavalapati (2004) assessed the effect of catastrophic risk on selling credits of carbon sequestration from a pine forest. More recently, Creamer et al. (2012) investigated forest carbon sequestration under wildfire risk and stochastic carbon prices. With regard to prescribed burning, only a small number of studies have analyzed its impact on forest management. For instance, Hesseln (2000) reviewed the economic literature pertaining to prescribed burning, especially its costs, benefits and risk. Yoder (2004) analyzed the economics of prescribed burning for mitigating wildfire risk with a modified Faustmann model. Overall, wildfires have been analyzed more thoroughly than prescribed burning.

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* Corresponding author.
E-mail address: cs258@msstate.edu (C. Sun).

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Existing carbon policies, such as the Clean Development Mechanism in the Kyoto Protocol, have been largely ambiguous about the interplay of wildfires and prescribed burning in carbon accounting. Thus, the objective of this study is to examine the effect of different hypothetical carbon policies on forest management decisions of harvesting rotation, planting density and prescribed burning under the risk of wildfires. Four carbon policies are designed in this study, with differences in the accounting rules when carbon is released from a forest stand by harvests, wildfires and prescribed burning. The analysis is conducted at a stand level with a generalized Faustmann model. By choosing different management decisions, a landowner is allowed to optimize the land expectation value which includes both timber revenue and carbon credit. The research findings are expected to reveal the relation between carbon policies and landowners' behavior, which can help government agencies improve carbon policy designs.

2. Theoretical model and carbon sequestration

The optimal rotation age of a single forest stand has been a classic problem in forest economics (Amacher et al., 2009). In 1894, the Faustmann model was developed to obtain the optimal harvesting rotation (T) for the first time by maximizing the land expectation value function $V(T)$ (Faustmann, 1995). In the past several decades, this model has been extended to analyze various issues in forestry such as taxation, planting density and wildfire risk. In this study, the Faustmann model is employed to assess the impact of different carbon policies on landowners' management decisions. The standard Faustmann model is first extended to form the base scenario or model. Both wildfire risk and prescribed burning are considered in the base model and a total of four choice variables are allowed. Two of them are ordinary management variables: harvesting rotation age (T; years) and planting density (D; trees per acre), and two others are related to prescribed burning: the time (S; years after the stand's establishment or regeneration) and intensity (Z; an index). In the model, a Poisson stochastic process is adopted to describe the probability of wildfire occurrence (Reed, 1984). When a homogenous or non-homogenous Poisson process is assumed, wildfire risk can either be independent or dependent of the stand age (Amacher et al., 2009). Then, four carbon policies are designed and incorporated into the base model. In the end, all the models are simulated with selected function forms and parameters, and for each of the policies, optimal strategies are derived and compared with those from the base model.

2.1. The base scenario with wildfires and prescribed burning

The Faustmann model was initially developed to help a landowner make management decisions on a homogenous forest stand. In general, it is assumed that a landowner faces an infinite series of rotations on the forestland and he is risk-neutral (Amacher et al., 2009). To begin with, assume at the stand level that every rotation ends at the age T, management cost is zero, timber volume at the harvesting time is Q^w thousand board feet (MBF) per acre, timber price is P^w ($/MBF), and r is the interest rate for continuous discounting (%). For an infinite sequence of identical rotations, the net present value of the forestland can be expressed as

$$V(T) = \frac{Q^w P^w e^{-rT}}{1-e^{-rT}} \quad (1)$$

which is also referred to as the land expectation value. The classic problem for a landowner is to maximize this value with regard to the rotation T.

The above standard Faustmann model has been extended to allow a landowner to make more choices besides the rotation age. In this study, three new choices are incorporated into the model: planting density, time and intensity of prescribed burning. In addition to timber volume, the choice of planting density affects fuel accumulation, which in turn influences the damage after a wildfire (Amacher et al., 2005). Prescribed burning is assumed to be applied at most once in the S-th year of each rotation with the intensity Z as an index. If a wildfire occurs after the application of prescribed burning, it is assumed that the stand can be partially salvaged, and both the time S and intensity Z will affect the salvage percentage. Thus, the land expectation value becomes a function of four choices as $V(T, D, S, Z)$.

To expand the above standard model, both wildfires and prescribed burning are considered in this study, which serves as the base model. Wildfire risk is inherent in forest management (Reed, 1984). Because the occurrence and time of a wildfire are stochastic, the Faustmann model is not deterministic anymore. It implies that a probability function has to be employed to calculate the land expectation value. First of all, a random variable X is defined to represent the time when a stand ends by either a wildfire ($X< T$) or a final harvest ($X=T$). Furthermore, including prescribed burning in the model will result in three possible states, depending on the relationship between S, T and X: (1) a wildfire occurs before prescribed burning ($X<S$); (2) a wildfire occurs after prescribed burning but before a final harvest ($S<X<T$); and (3) no wildfire occurs before a final harvest ($X=T$).

In State 1, no prescribed burning is applied before the wildfire, so it is assumed that the occurrence of a wildfire will destroy the stand completely and the timber left does not have any salvage value. This is reasonable when a stand is very young and the value of standing timber is limited, no prescribed burning has ever been applied, but a wildfire occurs early during a rotation. In State 2, given that the stand is treated by prescribed burning already, it is assumed that the occurrence of the wildlife will destroy the stand partially and a salvage harvest can be applied instantaneously after the wildfire. In State 3, no wildfire occurs so the landowner can harvest all the timber with a complete rotation. The landowner pays for the cost of replanting regardless of the state, and additionally under States 2 and 3, for the cost of prescribed burning. Mathematically, the current returns ($/acre) at the end of a random rotation in the three states can be expressed respectively as:

$$\begin{aligned} V_{01} &= -H_2^w \\ V_{02} &= Q^w P^w \sigma - H^R e^{r(X-S)} - H_2^w \\ V_{03} &= Q^w P^w - H^R e^{r(T-S)} - H_1^w \end{aligned} \quad (2)$$

where the subscripts in V_{01}, V_{02} and V_{03} denote the base scenario 0 and States 1, 2 and 3; σ is the salvage percentage over the total timber volume when a wildfire occurs under State 2; H_1^w is the replanting cost ($/acre) on the unburned land after a final harvest ; H_2^w is the replanting cost on the burned land after a wildfire, without or with a following partial salvage harvest; H^R is the cost of prescribed burning ($/acre). The timber price P^w ($/MBF) is assumed to be constant in the study. The factor of $e^{r(X-S)}$ or $e^{r(T-S)}$ converts the cost of prescribed burning at the time of application toward the end of a rotation, so all the values are current and addible at the end of a rotation.

The variable X and the current return functions under the three states allow us to calculate expectation value of the stand when wildfire risk is taken into consideration. Compared to Eq. (1), the problem for the landowner becomes:

$$\max_{T,D,S,Z} \frac{E(e^{-rx}V(X))}{1-E(e^{-rX})} \quad (3)$$

where $E(\bullet)$ is the expectation symbol. The objective is to obtain the maximum value of Eq. (3) given the distribution of X. Following the transformation in Englin et al. (2000) and Amacher et al. (2005), the above equation can be expressed as:

$$V_0(T,D,S,Z) = \frac{\int_0^S \lambda(X) B V_{01}\, dX + \int_S^T \lambda(X) B V_{02}\, dX + e^{-m(T)-rT} V_{03}}{r \int_0^T B\, dX} \quad (4)$$