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A generalized Reed model with application to wildfire risk in even-aged Southern United States pine plantations

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ABSTRACT

We develop a generalized Reed model to incorporate the risk of wildfires on optimal management of slash pine (*Pinus elliotti* var. *elliotti*) in the southern United States. Comparative static analyses are conducted to determine the impacts of the probability of increasing and constant wildfire risk as forest stand ages, and portion of stand that is salvageable following a wildfire, on slash pine harvest decisions. Our results reveal that increasing the current risk of wildfire damage would shorten the current optimal slash pine harvest age, while increasing the future risk of wildfire losses would lengthen the current optimal harvest age. We also compare the impacts of different wildfire arrival paths (rising and constant arrival rate with stand age) on the optimal forest management of slash pine. Under the generalized model, increases in future rising wildfire risks have less impact than increases in future constant wildfire risks on the optimal harvest ages for the current crop. Increases in the current rising risk of wildfires have a similar impact on the optimal harvest age compared to increases in the current constant risk of wildfires.

1. Introduction

The Faustmann model, published in 1849 (Faustmann, 1849), describes the forest owner's problem of selecting the rotation age that maximizes the net present value of forest-related cash flows. A major limitation of the model is its deterministic nature. Risks related to natural hazards such as hurricanes, wildfires, flooding, pest outbreaks, ice storms and droughts influence forest management decision making (Amacher et al., 2009); yet the classic Faustmann model fails to incorporate these risks.

Reed (1984) adapted the Faustmann model to explicitly incorporate risk from natural hazards. His model assesses the effect of catastrophic event risk on optimal timber harvesting and profitability of a forest stand embedded within a Faustmann framework. This approach has been widely used to determine optimal forest management, mainly for risk of fire (Reed, 1984; Reed and Errico, 1985; Susaeta et al., 2009). Englin et al. (2000) included amenity values subject to the risk of fire. Stainback and Alavalapati (2002) adapted the Reed model to incorporate payments for carbon sequestration. Amacher et al. (2005) extended the Reed model by incorporating fuel reduction decisions and modeling timber salvage as a function of stand density and fuel reduction treatments to protect forest landowners against losses.

One of the limitations of the traditional Reed model is that real stumpage prices, stand volume and real regeneration costs are assumed to be constant for all harvest time periods. Instead, these parameters are likely to vary between timber crops,[1] thus the harvesting decision is also expected to change over successive timber crops. Two salient parameters of the Reed model are the probability of a catastrophic risk event and the salvageable portion of the damaged timber crop. Both parameters are also likely to change over successive timber crops. Age, biological, and ecological conditions of the forest stand may also influence the probability of a natural hazard (Amacher et al., 2009; Reed, 1984) and the possibility of salvage operations (Amacher et al., 2005; Amacher et al., 2009). For example, older timber stands that have accumulated flammable woody material would be more prone to wildfires (Li et al., 1997). Temperatures are expected to rise over time due to climate change, and with that come a whole host of expected climate related impacts, including increased risk of hurricanes, wildfires, and pests.

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[1] For example, forest stumpage prices are widely acknowledged to vary as timber crop ages due to different mixes of forest products. Forest growth and thus stand volume are influenced by silvicultural treatments and external factors such as climate and risk events which are likely to vary over successive rotations. For example, loss in productivity of the forest stand after several rotations is associated with intensive site and harvesting operations (Evans, 2009). Further, the development of new technologies (Saarinen, 2006) or changes in tree density over successive rotations may alter forest regeneration costs.

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Climate change would likely result in more intensive future storms in general (Karl et al., 2009). The probability of wildfires and invasive species may increase after a hurricane (Myers and Van Lear, 1998). Current and future macroeconomic conditions and reduction in fuel loads would also influence timber salvage operations. Increased salvage logging would be expected as higher returns are realized (Prestemon and Holmes, 2008). Salvage logging intensity might also decline if it negatively affected the forest stand structure, ecosystem process, and community composition (Lindenmayer and Noss, 2006).

We present, unlike previous studies, a generalized version of the Reed model that accounts for not only risk of natural hazards but also allows all other factors to vary between different timber crops. The novelty of this generalized model–as opposed to the traditional Reed model–lays in the capacity to incorporate the impact of risk of future natural hazards, and future salvage possibilities on the current landowners' harvesting decision, within the context of wildfire events.[2]

The dynamic nature of future natural hazards given expected changing climatic conditions is an essential component of the complex decision-making process for forest landowners (Yousefpour et al., 2012). With higher expected fire activity in the South's spring season over the 21st century, due to global warming conditions (Bedel et al., 2013), the future investment in forestry and current optimal forest management will be undoubtedly impacted. Our model allows for the analytical estimation of profitability of forestlands and current harvesting decision from wildfire events expected to affect current and future timber crops. Given the influence that wildfire events have on forest management decisions, and concerns that climate change may exacerbate risks related to this natural disturbance, the flexibility of our stand-level model would permit closer examination of event impacts on forestry decision making.

This paper is organized as follows: first, we outline the underlying features of the traditional Reed model and followed up with the development of the generalized Reed model. Next, using the generalized model, we ascertain the effects of catastrophic current and future risks on the optimal harvest age for the current stand. We then discuss the historical effect of wildfires on southern U.S. forestlands and apply the model to a representative southern pine species–slash pine (*Pinus elliotti* var. *elliotti*)–and discuss the results. We also contrast the impacts of different wildfire arrival paths on the optimal forest management of slash pine. Finally, we offer some concluding remarks and recommendations for further research.

2. Derivation of the generalized Reed model

2.1. The traditional Reed model

Reed's classic economic model (Reed, 1984) incorporated the effect of risk of a catastrophic event and salvageable portion of the forest into the Faustmann model. Reed (1984) assumed that the catastrophic event followed a non-homogenous Poison process, with and distribution parameter λ dependant on forest stand age,[3] $\lambda = \lambda(X)$. The λ parameter represented the probability of occurrence of a fire in any given year. We also assumed a rising rate of damaging fire arrival as forest stand ages, i.e., $\lambda'(X)>0$. It is further assumed that the time between successive fires events–the age of the stand at the time when fires occurs–was a random variable X that followed an exponential distribution with cumulative density function $1 - e^{-m(X)}$, where $m(X) = \int_0^X \lambda(q)dq$ and is increasing in X, thus $\frac{dm}{dX} = \lambda(X)$. The probability that a fire event may affect a forest stand before reaching the economically optimal rotation age T was $\Pr(X<T) = 1 - e^{-mT}$ and the probability of the stand reaching the optimal rotation without being affected by a fire event was $\Pr(X = T) = e^{-mT}$. The probability density function of X before reaching the optimal rotation age $(0 < X < T)$ is given by $\lambda(X)e^{-mX}$.

Thus, the net revenues for a forest landowner would depend on two states of the world. In the first state of the world, a catastrophic event (i.e., wildfires) arrives at time t before the stand could reach the optimal rotation age T. Following the event, the landowner salvages a random proportion $g(t)$ of the forest with mean $\overline{g}(t)$ and incurs the regeneration costs (C) associated with the new forest stand. In the second state of the world, the landowner receives the net returns from harvesting the forest stand at the optimal rotation age without being affected by a wildfire, and incurs the replanting costs (C) for a new forest stand. Assuming that the time between successive stand harvest and/or destruction is X_n for n rotations, and P and $Q(T)$ represent the stumpage price, and volume of the stand at time T, respectively, we obtain the following net economic revenues Y_n for the first rotation:

$$Y_n = \begin{cases} \overline{g}(X_n)PQ(X_n) - C & \text{if } X_n < T \\ PQ(T) - C & \text{if } X_n = T \end{cases} \tag{1}$$

Following Reed (1984) it is assumed that a landowner will have to harvest the stand at the optimal rotation age and replant to start a new rotation, or salvage a proportion of the stand in face of a catastrophic event and replant. This process continues ad infinitum. Thus, the sum of net present economic returns due to either harvesting or salvaging undamaged timber of equal successive rotations in perpetuity (land expectation value LEV) is as follows:

$$LEV(T) = \frac{E(e^{-rX}Y)}{1 - E(e^{-rX})} = \frac{[PQ(T) - C]e^{-(rT + m(T))} + \int_0^T \lambda(X)[\overline{g}(X_n)PQ(X_n) - C]e^{-(rX + m(X))}dX}{\frac{re^{-(rT + m(T))}}{\lambda(T) + r}}. \tag{2}$$

where r is the real discount rate. The time T that maximizes the LEV is the optimal rotation age. The full derivation of this model can be found in Reed (1984).

2.2. The generalized Reed model

To derive a generalized Reed formula, we follow similar assumptions developed by Reed (1984) with the caveat that, as evidenced in the Introduction section, the parameters are unlikely to be the same from harvest to harvest. For each timber crop, a landowner will have to replant a new timber crop regardless of the event (stand harvest or salvage due to fire arrival), facing different levels of stumpage prices and forest growth, regeneration costs, discount rates, wildfire risk, and salvageable portions. Thus, the optimal harvest age is also expected to fluctuate from timber crop to timber crop. For simplicity's sake we assume that regeneration costs, and real discount rate to vary from timber crop to timber crop but independently of the age of the trees.

We assume that fluctuations of stumpage prices and volume of the forest stand from timber crop to timber crop also depend on the age of the forest stand.[4] In the case of the salvageable portion, it has been considered difficult to model (Reed and Errico, 1985). Amacher et al. (2005) have modeled it as an increasing and decreasing function, respectively, of intermediate treatments and tree density. In our particular

[2] Wildfires represent a major economic threat in the U.S. Wildfire suppression expenditures by the United States Forest Services totaled, on average, $1.2 billion annually between 2001 and 2010 (Stein et al., 2013). Total costs of six weeks of large wildfires in Florida accounted for $522 million to $762 million in 1998 (Stein et al., 2013).

[3] Reed (1984) also assumed that fire risk follows a homogenous Poisson distribution, i.e., the fire arrival is not dependant on the forest stand age. Other studies such as Stainback and Alavalapati (2004) and Susaeta et al. (2009) also considered that the disturbance risk does not vary with the age of the trees.

[4] As the forest stand ages different proportions of forest products are obtained with different prices. We have not considered changes in stumpage prices over the rate of inflation in our analysis. For stochastic stumpage prices (real option theory) see Gjolberg and Guttormsen (2002), and Insley and Rollins (2005).