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Analysis

Managing Forests for Carbon and Timber: A Markov Decision Model of Uneven-aged Forest Management With Risk

Craig M.T. Johnston [a],*, Patrick Withey [b]

[a] Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, 1630 Linden Drive, Madison, WI 53705, United States
[b] Department of Economics, St. Francis Xavier University, PO BOX 5000, Antigonish, NS B2G 2W5, Canada

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ABSTRACT

This paper calculates steady state management decisions that, if followed indefinitely, provide an adaptive strategy that maximizes the value from timber and carbon sequestration when risk is present. By including carbon offsets directly in the objective function of a Markov decision process (MDP) model, we find long-term trade-offs exist between economic and ecological outcomes. An economic supply schedule is provided, which shows an exponential increase in the cost of sequestration. Moderate carbon prices effectively sequester additional CO_2 from the atmosphere while having a positive impact on ecological indicators such as size and species diversity. In contrast, high carbon prices promote more of a monoculture in order to maximize expected forest value in the long run from carbon sequestration. This study finds evidence that the optimal adaptive decisions are sensitive to the magnitude of carbon prices, and consequently, so too are ecological outcomes. While some governments acknowledge the influence carbon markets have on the ecological integrity of the forest, fluctuations in carbon prices within a cap-and-trade market likely influence the optimal decision making of the forest manager, and thus, the ecological landscape of the forest itself.

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1. Introduction

Societal interest in climate change mitigation has opened the door for forest management to play an integral role in reducing atmospheric CO_2. Terrestrial ecosystems represent two-fifths of the total exchange of CO_2 between earth and the atmosphere, with forests accounting for 80% (FAO 2014). Clearly, forests are critical in determining the concentration of CO_2 in the atmosphere, with human activities related to forest management affecting the globe's CO_2 balance. With this in mind, forests can be managed to produce carbon offsets to nullify or offset the impact of a carbon emitting activity (see van Kooten & Johnston, 2016), facilitated through programs such as the Clean Development Mechanism (CDM) that were introduced to help member nations meet their self-imposed Kyoto targets (see Armano & Sedjo, 2003).

Forest management can also significantly affect the ecological landscape. A common approach in forestry is to employ even-aged management that promotes clear-cut harvesting of stands of similar age, size and species. While this method is economically favorable in many cases, it is often criticized for failing to preserve the ecological integrity of the forest (Esseen et al., 1992; Kuuluvainen, 2002; Doyon et al., 2005; Xabadia & Goetz, 2010). Consequently, there is increasing interest in managing the forest for both timber and carbon production, while at the same time, maintaining a more diverse stand structure. Uneven-aged forest management can be used to achieve the best outcome given these competing goals. Such methods include thinning, or only harvesting certain species in certain diameter classes, promoting the ecological integrity of the forest (Kuuluvainen et al., 2012). While more knowledge is required for this management strategy, it can achieve the joint goals of managing forests for profit as well as ecological diversity.

Still, relatively little is known of the long term economic and ecological outcomes of uneven-aged forest management when carbon has value, particularly when accounting for risk in forest growth and market conditions. Early studies extended traditional Faustmann models, which examine optimal replant intervals, to include annual ecosystem benefits (Hartman, 1976) and later to include carbon sequestration (van Kooten, 1995). These models assume even-aged forest management, and examine the trade-off between harvesting for profit and ecosystem services (Gutrich & Howarth, 2007). Van Kooten (1995) established that placing value on forest carbon offsets leads to longer rotations and increased carbon sequestration. However, uncertainties involving the effect of disturbance on the production of such offsets still exist, and this can significantly affect forest planning and ultimately the long-term ecological qualities of the forest (Kurz et al., 2008; Lindroth et al., 2009).

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* Corresponding author.
E-mail address: craig.johnston@wisc.edu (C.M.T. Johnston).

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The literature concerning the role of risk in forest management is well established (see. e.g. Kant and Alavalapati, 2014, pp. 307–369). Studies that have extended Faustmann models examine the impact of uncertainty on forest management, including risk related to forest growth, as well as uncertainty in timber and carbon markets, and the impact of risk aversion (see Alvarez & Koskela, 2004; Ruszczynski, 2009). Hu (2014) outlines several studies that examine the effect of catastrophic events on optimal forest rotations, but few applications have considered risk and uncertainty in forest carbon offset production. Chladni (2006) develops a real options model that includes stochastic wood and carbon prices that follow a mean reverting process. Like the previous studies, their analysis focuses on whether stochastic prices will affect the optimal rotation model, assuming even-aged forest management. They find that the optimal even-aged rotation age varies with the way the stochastic price processes are defined.

As mentioned above, since historical management practices such as clear cutting can have adverse effects on ecosystem services, there is increasing interest in uneven-aged forest management as an alternative to clear cutting methods. Several recent studies have developed nonlinear matrix growth models that predict stand growth for different species and size classes of trees (Ralston et al., 2003; Liang et al., 2005), as well as accounting for uncertainly related to weather and pests (Liang et al., 2006). Such growth models have formed the basis of Markov decision process (MDP) models used to find the optimal harvest decisions that maximize the forest value in an environment with multi-dimensional risk (Zhou and Buongiorno, 2011).

While uneven-aged models have been used to account for uncertainty in stand growth, timber prices and interest rates (Zhou et al., 2008; Zhou and Buongiorno, 2011), they have been relatively absent in the literature concerning the ecological effects of placing value on carbon in an uncertain environment. Two studies should be noted. The first is Buongiorno et al. (2012) who place value on carbon in an uneven-aged framework, highlighting the impact on stand structure including the diversity of tree size and species, as well as carbon stocks. This study does not consider uncertainty associated with disturbance and does not provide optimal decisions in a stand-state formulation. The other study is Buongiorno and Zhou (2015) who investigate uneven-aged management with uncertainty associated with disturbance, highlighting economic and ecological trade-offs associated with optimal decision making under risk. Yet, the authors do not include carbon prices directly in the objective function, which prevents conclusions to be drawn on the effects of carbon offset markets on the ecological quality of the forest when faced with risk.

With this in mind, we extend these methods to investigate the impact of uneven-aged forest management when carbon has value. Washington and Oregon state provide a nice case study as they contain a significant proportion of US timberland, and consist of highly productive softwood species, such as Douglas fir (*Pseudotsuga menziesii*) and Western hemlock (*Tsuga heterophylla*). Forests in the Pacific North West (PNW) also provide substantial environmental benefits, including wildlife habitat, ecosystem diversity, recreational use and carbon sequestration. This study builds on the current literature by expanding a forest management model of the PNW region (Zhou et al., 2008), taking into account stochastic disturbances to stand growth based on past behavior of ecological and climatic shocks. It is the first known study that examines the trade-off between carbon sequestration (using carbon prices) and timber in an MDP model, by explicitly including the value of carbon storage in the objective. We can therefore examine how incorporating the value of carbon will impact optimal silviculture strategies.

The main contribution of the paper is to include the value of carbon in a MDP model, and determine optimal management regimes and the impact on long term economic and ecological outcomes when carbon prices change. These outcomes include optimal cutting cycles, the value of the land, carbon storage and ecological diversity. Results of the analysis indicate that as carbon prices rise, forest value is estimated to increase. There are also more incentives to either thin the forest or let the forest grow rather than clear cut, resulting in higher standing volume in the forest as carbon prices rise. Moderate carbon offset prices promote size and species diversity, but for carbon prices above an estimated \$21.50 tCO_2^{-1}, the forest begins to be managed primarily for carbon sequestration value, and while additional CO_2 is sequestered, species and size diversity appear to be compromised.

2. Methods and Data

The guiding principle of this study is to represent the evolution of the forest ecosystem based upon biophysical variables subject to random disturbance using Markov chains: a random process that describes the frequencies of transition from one state to another on a state space. One can use a Markov decision process (MDP) model to predict the future of the forest state space subject to optimal management strategies and random disturbance. The management strategies are a set of rules that describe a decision for each observed state space, and therefore may provide adaptive strategies for achieving different objectives. The novel contribution of this paper is to add carbon prices to the MDP framework, as outline in Section 2.3.

2.1. Growth Model Structure

This study builds upon the stochastic growth model and MDP model from Zhou et al. (2008), which is based on previous work developed in Ralston et al. (2003) and Liang et al. (2006). The model predicts stochastic stand growth from 14,794 FIA plots, covering both public and private forestlands in the state of Oregon and Washington from 1988 to 2000 (Table 1). The stand states of the forested landscape are described by the level of basal area in trees of different sizes and species, with basal area in three tree size classes: small (10 cm ≤ dbh < 25 cm), medium (25 cm ≤ dbh < 41 cm), and large (dbh ≥ 41); and two species categories (shade tolerant, shade intolerant). Basal area can take on two levels, high or low, indicating above or below average basal area in a given size and species class. The threshold between low and high basal area was based on the average basal area in each species and diameter category. For shade-tolerant species, these values equaled 5.85, 5.37, ad 5.39 m^2 ha^{-1} for small, medium and large trees, respectively. The corresponding thresholds for shade-intolerant species were 3.25, 2.48, and 2.84 m^2 ha^{-1}. Thus, there are $2^6 = 64$ possible stand states; each stand state is described by a string of six digits. For example, consider stand state 001010 where the first three digits correspond to shade tolerant trees with low basal area in small and medium sized trees, but above average basal area in the large trees. The last three indicate shade intolerant species with below average basal area for small and large trees, and high basal area in medium trees.

The probability matrix that describes the frequencies of transition from state s to s' is described by $\mathbf{T} = [p(s'|s)]$. These transition probabilities are taken from Zhou et al. (2008), who employ the following stochastic simulation model of stand growth:

$$\mathbf{y}_{t+1} = \mathbf{G}_t\mathbf{y}_t + \boldsymbol{r_t} + \mathbf{u}_t, \tag{1}$$

where $\boldsymbol{y}_t = [y_{ijt}]$ is the number of trees per unit area of each species group $i = 1, \ldots, m$ and diameter class $j = 1, \ldots,$ n at time t. $\mathbf{G}_t$ is a state-dependent matrix that describes the probability that a tree of a given species stays alive and grows into a higher size class from t to $t + 1$. $\mathbf{r}_t$ is a measure of recruitment; the number of trees that enter into the smallest age class from t to $t + 1$. Finally, $\mathbf{u}_t$ is a vector of random disturbance.

The observed disturbances were calculated as the difference between the number of trees estimated by model (1), and the observed number of trees according to the FIA plots. This difference gave rise to a vector of random shocks $\mathbf{u}_t$. The random disturbance included in the growth model is based on observed data and captures risk to growth such as extreme weather events or pests, which have affected forest

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