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Adapting sustainable forest management to climate policy uncertainty: A conceptual framework

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ABSTRACT

Sustainable forest management delivers ecological benefits critical to mitigating climate change impacts and can produce carbon offset credits tradable at the market price, generating additional income to forest landowners. However, due to high uncertainty in the climate policy of the United States, the economic potential of sustainably managing forests for offset credits is uncertain, discouraging landowners from participating in such practices. Also uncertain are the ecological consequences, especially in terms of forest carbon stocks. Here a conceptual framework was proposed which, with a regime-switching process, modeled the price of carbon credits as a proxy of the climate policy. Uncertainty in policy was translated into a limited number of *scenarios* regarding the *timing* and *magnitude* of policy regime switches. This model was then incorporated into a Markov decision process model of forest management, which accounted for multiple forms of risk and uncertainty affecting forest functioning and management. Using linear programming, this framework quantified the economic and ecological potentials of forest carbon management in various policy *scenarios* and determined optimal harvesting rules adaptive to policy shifts. A simple numerical example was provided to demonstrate the application of this framework.

1. Introduction

Forests, as the largest natural terrestrial carbon sink, play an essential role in the global carbon cycle. Recently, sustainable management that keeps or raises forest carbon stocks has been recognized as one of the critical tools to mitigating climate change impacts by continuously producing fiber, timber, and biomass (IPCC, 2007). With the emergence of market-based mechanisms for mitigation, by increasing carbon stocks, forest management can also produce carbon offset credits tradable at the market price, which in turn generates additional income to forest landowners.

However, political, social, economic, and technological factors, along with uncertain rate and magnitude of global climate change (IEA, 2007), contribute to high uncertainty in climate policies. This is especially the case for the United States because it has not ratified international climate change treaties and has yet to establish a national mandatory framework of greenhouse gas emission reduction through trading, taxation, or a combination thereof. Therefore, the movement of the price placed on greenhouse gas reduction or sequestration (hereafter, carbon price) is largely uncertain and so is the economic potential of managing forests for offset credits. The involved risk particularly discourages private forest landowners from participating in such management practices (Galik and Jackson, 2009). The problem gets more complicated when disturbances to forest functioning and management come into play. A comprehensive framework that takes into consideration multiple factors of risk and uncertainty and is still capable of solving large-scale practical problems is much needed yet absent.

Policy uncertainty, although highly relevant to many real-world decision-making problems, has been investigated only to a limited extent, and empirical applications are scant. One difficulty lies in modeling policy switches with standard stochastic processes, partly because major policy regime shifts have low frequencies (Zadeh, 1965). Some successes have been achieved by using the Poisson jump process to represent the introduction and removal of a policy (e.g. Hassett and Metcalf, 1999; Barro, 2006). An alternate approach is to model measurable or observable variables as proxies for policy uncertainty, which has extended applications in economics. For example, Baker et al. (2012) construct an index of economic policy uncertainty with three components including search results of relevant keywords on Google News. Regime switching processes have been used for modeling the movement of economic variables under direct impacts of abrupt policy changes, for example, prices and interest rates, and have proven their utility in many case studies (e.g. Davig, 2004; Sims and Zha, 2006).

Climate policy uncertainty, acknowledged by many (Marcucci and Turton, 2012), has received considerable attention in quantitative risk analysis and decision making, but the majority of such studies deals with the energy industry (e.g. Neuhoff, 2007; Fuss et al., 2009; Krey et al., 2009; Kettunen et al., 2011; Krey and Riahi, 2013; Ngwakwe and

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Moyo, 2014). For instance, Sullivan and Blyth (2006) point out that climate policy uncertainty delays power plants' investment in "green energy". Patiño-Echeverri et al. (2009) and Patiño-Echeverri et al. (2007), respectively, derive the optimal investment and operating strategies for power plants, given uncertain carbon prices and timing of CO_2 emission regulations. The former also quantifies the economic cost and environmental impacts associated with such uncertainty. Another study of investments in power sector uses the carbon price as the climate policy proxy as well and assumes "a price jump in the range of $\pm$100% with a flat probability within this range" if a regime change is going to happen in five or 10 years (Blyth et al., 2007). Ådahl and Harvey (2007) examine financial and environmental consequences of energy efficiency measures of pulp mills for four possible climate policy scenarios represented by various emission targets and charges.

In the forest sector, the efficacy of management on combating climate change impacts has been widely acknowledged. Malmsheimer et al. (2011) provide a comprehensive overview while making recommendations to the U.S. climate policymaking. There exist some deterministic studies from the economic and ecological standpoints by applying simulation and optimization approaches (Huang and Kronrad, 2001; Sohngen and Mendelsohn, 2003; Birdsey et al., 2006; Gutrich and Howarth, 2007; Yousefpour and Hanewinkel, 2009; Buongiorno et al., 2012). From the social perspective, landowners' attitude to and participation in sustainable management and carbon offset have been to some extent studied (Shaikh et al., 2007; Markowski-Lindsay et al., 2011, 2012; Soto and Adams, 2012). However, the link is often missing between the proposed management guidelines and the attitude, objectives, and constraints of landowners in reality.

Galik and Jackson (2009) offer a descriptive overlook of risk and uncertainty involved in forest carbon offset projects, but quantitative examinations of multiple sources of uncertainty and risk, especially policy uncertainty, remain inadequate, with the following exceptions. At the macro level, Schneider and McCarl (2003), within the Agricultural Sector Model (ASM) and the Forest and Agricultural Sector Optimization Model (FASOM), change the carbon price from zero to $500 per ton in $20 increments and study the response of multiple variables to such variations. The variable of most relevance to this study is the estimated amount of tree carbon sequestration. Latta et al. (2011) simulate mandatory and voluntary participation of private landowners in carbon offset programs with a number of carbon prices and quantify the consequences on forest carbon cycles, stocks, harvests, and stumpage prices. At the stand level, most existing work focuses on one single source of risk. Stainback and LAVALAPATI (2004) examine the effect of catastrophic events on the land expectation value and optimal rotation for pine plantations under changing carbon prices. Couture and Reynaud (2011) and Daigneault et al. (2010) in a similar context, study the effect of forest fire risk in particular. Niemiec et al. (2014) show how the optimal management of forest insects changes with different carbon prices and their growth rates when CO_2 sequestration is part of the nontimber services in consideration.

Quantitative considerations of other stochastic sources affecting forest functioning and management are crucial to our overall understanding but present considerable computational challenges. Stochastic growth and management models have been developed based on deterministic models to account for biological disturbances and economic fluctuations. In general, two types of stochastic elements have been used to account for environmental variability (Fieberg and Ellner, 2001; Kaye and Pyke, 2003; Ramula and Lehtilä, 2005; Liang and Picard, 2013): resampling and parametric distribution (e.g. Dalgleish et al., 2010), and stochastic shocks (e.g. Jiang and Shao, 2004; Zhou and Buongiorno, 2004; Zhang et al., 2013). A model of this type can be applicable to forest management through simulations (Buongiorno and Gilless, 2003, Chap. 14 & 15). However, the derivation of optimum management from simulations, for example, with response surface analysis (Liang et al., 2006), can be too computationally intensive even for small-scale projects.

A simpler and computationally less intensive way of describing stochastic forest growth and yield is with discrete-time finite-state Markov chains (e.g. Hool, 1966; Lembersky and Johnson, 1975; Lin and Buongiorno, 1998; Jenkins et al., 2003). The basic idea is to define a set of exhaustive forest stand states to recognize any forest condition at a certain point in time, and describe the transition between states during some fixed interval with a matrix of probabilities. Markov chain models lend themselves readily to optimization in the form of Markov decision process (MDP) (Puterman, 2009). One attractive feature of MDP models is that they have closed form solutions and are capable of dealing with large problems, especially of multiple rotations, efficiently through linear or dynamic programming. In addition to early applications of MDP models in forest management which recognize risk in forest growth and yield (e.g.Hool, 1966; Lembersky and Johnson, 1975; Lembersky, 1976; Kaya and Buongiorno, 1987, 1989; Lin and Buongiorno, 1998; Zhang et al., 2013), fluctuating timber prices have also been taken into consideration (Zhou et al., 2008). Most recently, Buongiorno and Zhou (2011) and Zhou and Buongiorno (2011) further extend the MDP models to include risk in the interest rate.

This paper was aimed at developing a conceptual framework to address both uncertain *timing* and *magnitude* of policy regime switches and determine the associated economic and ecological consequences, while accounting for multiple sources affecting forest functioning and management. We used a two-regime switching model of the carbon price, one as the proxy of the current regime of voluntary reduction, the other of mandatory reduction. A set of *scenarios* was constructed with uncertain *timing* represented by different values of discretized switching probabilities and uncertain *magnitude* by various future carbon prices. This regime switching model was then combined with a MDP model of forest management, which with linear programming, solved for the optimal decision variables that maximized the net present value of incomes from both timber and carbon credits, and determined best management practices in different *scenarios*. For illustration, a simplified forest stand consisting of six conditions was examined with the proposed approach. A fixed timber price was assumed in order to give emphasis to impacts of uncertain carbon prices. Linear programming was then used to solve this example to illustrate the policy effects on the net present value of combined timber and carbon credit incomes and expected carbon storage in the short-, medium-, and long-run.

2. Methodology

2.1. Modeling climate policy uncertainty

To describe the shift of U.S. domestic climate policies, a two-regime switching model was set up as follows:

$$\begin{aligned}
&P(R_t = \mathbf{1} | R_{t-1} = \mathbf{1}) = 1-\alpha \\
&P(R_t = \mathbf{2} | R_{t-1} = \mathbf{1}) = \alpha \\
&P(R_t = \mathbf{2} | R_{t-1} = \mathbf{2}) = 1-\beta \\
&P(R_t = \mathbf{1} | R_{t-1} = \mathbf{2}) = \beta \\
&0<\alpha<1, 0<\beta<1
\end{aligned} \tag{1}$$

where **1** represented the current regime of voluntary reduction; **2** the future regime of mandatory reduction. R_t was the policy regime at time *t*, and P (R_t | R_{t-1}) represented the probability of switching from the policy regime at $t-1$ to the regime at *t*. The interval between $t-1$ and *t*, *l*, could be of any predefined length, but preferably should be consistent with the interval of forest management models which is in general in increments of years.

We used the carbon price in the unit of U.S. dollar per metric ton (*tonne*) of CO_2 equivalent ($/t$CO_2$-e) as the proxy of U.S. domestic climate policies as it is under direct influence of such policies. C_1 was the expected carbon price in Regime **1** and C_2 the expected carbon price in Regime **2**. C_1 can be estimated as the arithmetic or weighted average