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Carbon sequestration through afforestation under uncertainty

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ABSTRACT

Economic studies have demonstrated that agricultural landowners could mitigate significant quantities of greenhouse gas (GHG) emissions through afforestation. The associated carbon, however, must remain stored in soils or biomass for several decades to achieve substantial mitigation benefits. Policies and programs to enhance carbon sequestration in forest systems must accommodate the possibility of premature carbon releases. We develop a dynamic nested optimal-control model of carbon sequestration through afforestation given uncertainties associated with fire and pest hazards. Our framework highlights a number of factors that affect landowner decisions to invest in fire or pest prevention measures. For fire, we show the net influence of these factors is to encourage investment in prevention measures when the probability of fire occurring is less than the ratio of expected net economic benefits to expected gross economic benefits of adopting fire prevention measures. For pests, we show that landowners will invest in prevention measures when the probability of fire is less than the ratio of the difference between net benefits before and after the discovery of tree pests to the difference between gross economic benefits before and after the discovery of pests. For both risks, landowners will over-invest in prevention if the other risk is ignored.

1. Introduction

Numerous economic studies have demonstrated that agricultural landowners could mitigate significant quantities of greenhouse gas (GHG) emissions through afforestation — the shifting of cropland and pasture into trees (McCarl and Schneider, 2001; Lewandrowski et al., 2004; Lubowski et al., 2006; U.S. EPA, 2005). To realize the GHG mitigation potential of afforestation, however, farmers must be able to convert increases in carbon stored in soils and biomass to income. Several policy approaches could incentivize carbon capture through afforestation including the establishment of a carbon market (such as would occur under a state, regional, or national cap-and-trade program), the creation of a direct government payment explicitly for adoption of carbon sequestering practices (analogous to payments farmers receive under USDA's Conservation Reserve Program), and the development of voluntary carbon-related contracts between two or more private parties.

For afforestation to result in significant GHG mitigation, the associated carbon must remain stored in soils or biomass for an extended time (viewpoints range from 20 to over 100 years). As an example, the forest project protocol developed by the Climate Action Reserve for use in the California climate program requires: 1) afforestation/reforestation projects target lands not in forest cover during the previous 10 years; and 2) project lands remain in forest for 100 years (Climate Action Reserve, 2010). In policy and scientific settings this is referred to as the “permanence” issue.

Regardless of the policy approach, permanence has important implications for the design of carbon sequestration incentives. Specifically, incentives must accommodate both the possibility and uncertainty that carbon sequestered and credited within a mitigation framework may be prematurely released at some point in the future. Such releases could be unintentional (as in the case of a future fire event or a pest/disease outbreak) or deliberate (as in the case of a landowner decision to harvest timber prior to a previously agreed on date).

The premature release of carbon from a parcel of afforested land would likely create an obligation to either replace the released carbon or compensate the buyer — since it would already have been purchased and, presumably, used to meet a GHG mitigation commitment on the part of the buyer. Conceptually, the replacement obligation could rest with either the buyer or seller. For two reasons, we assume that it rests with the seller. First, sellers will typically be landowners and as such will have direct control over how afforested lands are actually managed. Putting the replacement obligation on landowners then creates an economic incentive for them to take specific land management actions that reduce the probability of a premature release. Second, buyers would likely be entities trying to meet specific emission reduction targets (for example, a private sector firm, industry or trade organization, or municipality that has made a public commitment to reduce its carbon footprint). If carbon sequestered through afforestation came with significant uncertainty regarding

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its permanence, these entities would likely look either to alternative suppliers of GHG mitigation or opportunities to reduce emissions within their own operation.

In this paper we examine the issue of permanence in the context of sequestering carbon through afforestation. We develop a dynamic nested optimal-control model of carbon sequestration associated with the decision to establish forest cover on a tract of land given the inherent uncertainties associated with fire and insect/disease hazards.[1] Conceptually, these hazards are similar in that their occurrence at any time t is uncertain and landowners can take specific actions — although generally different actions — to reduce the probability of sustaining related losses. The hazards differ, however, in that fire represents a large loss in carbon at a moment in time, while insect/disease (hereafter, "pest") infestations are more likely to display a period of gradual to significant slowing in the anticipated rate of carbon accumulation followed by a sustained period of steady carbon losses. The nature and uncertainties associated with these potential losses will influence: 1) the design of sequestration incentives under any GHG mitigation policy that requires premature carbon releases to be replaced or compensated; and 2) the set of actions landowners adopt to reduce the probability of such releases occurring.

The paper proceeds as follows: Section 2 briefly reviews timber production and risk management. An optimal-control model of timber production and carbon sequestration through afforestation under risk and uncertainty is presented in Section 3. Theoretical properties of optimal solutions are then discussed. Section 4 discusses optimal policies for budget allocation between fire preventive measures and pest preventive activities. Effects of adopting fire and pest preventive measures on carbon sequestration are discussed in Section 5. Section 6 provides summary and concluding remarks.

2. Timber production and risk management

Existing dynamic forest product models typically focus on production of timber and assume a point-of-input and point-of-output structure. Some more recent forest product models have added production of sequestered carbon with annual payments to landowners, but these generally assume a risk-free environment (van Kooten et al., 1995). More rigorous treatments that consider carbon sequestration and timber as jointly produced products need to reflect the inherent risks associated with forest fire and pest outbreaks.

Historically, response to the threat of forest fire has consisted of both preventive measures before forest fires occur and suppression activities once fires are detected. Preventive measures include various forms of monitoring (e.g., manned fire observation towers, aircraft, and satellite imagery) and activities that remove or reduce the quantity of combustible material on the forest floor and understory (e.g., removal of dead wood, controlled burns, and thinning). Suppression measures include a host of ground- and aerial-based fire-fighting systems. To model carbon capture in forest production under uncertainty, we use a modified hazard function approach to reflect risks and uncertainties associated with the timing of forest fires (Kamien and Schwartz, 1971; Kieffer, 1988; Kim et al., 2010). Define $M(t)$ to be the probability that forest fire occurs by time t, with $M(t=0)=0$, as:

$$M(t) = 1 - \exp[-\alpha m(F(t))]t, \;\; m(F(t=0)) = 0, \;\; \frac{\partial m}{\partial F} < 0, \;\; \alpha = \frac{1}{1+\sigma}; \tag{1}$$

where, $m(t)$ is the hazard rate, representing the conditional probability of a forest fire occurring during the next time period given that one has not occurred at time t, F is the preventive measures before the forest fire occurs, where $\frac{\partial F}{\partial t} \geq 0$, and $\sigma = \left(\frac{t}{m}\right)\left(\frac{\partial m}{\partial t}\right) \leq 0$, is the time elasticity of the conditional probability of forest fire. In Eq. (1), both the probability that forest fire occurs by time t and the conditional probability that forest fire will occur during the next time period, $t + \Delta t$, decline as fire prevention measures are adopted.

Using Eq. (1), the probability density function of the time for forest fire occurrence, $\frac{\partial M(t)}{\partial t}$, can be presented as the state equation:

$$\frac{\partial M(t)}{\partial t} = m(F(t))[1 - M(t)], \;\; \text{where} \;\; m(F(t=0)) = 0, \;\; \frac{\partial m}{\partial F} < 0; \tag{2}$$

Insect and disease pests are part of all forest ecosystems. However, landowners can take actions that reduce the likelihood of a pest outbreak occurring, and the damage done to standing trees if an outbreak does occur (e.g., selecting pest/disease resistant seedlings, prophylactic spraying, and other treatments to discourage pests and diseases from taking hold). Define $N(t)$ to be the probability that a forest pest (tree damaging disease or insect) is discovered by time t, with $N(t=0)=0$, as:

$$N(t) = 1 - exp[-\beta n(E_b(t))]t, n(E_b(t=0)) = 0, \;\; \frac{\partial n}{\partial E_b} < 0, \beta = \frac{1}{1+\gamma}; \tag{3}$$

where, $n(E_b)$ represents the conditional probability that discovery of the pest will occur during the next time interval $(t + \Delta t)$ given that one has not occurred at time t, E_b represents the preventive measures adopted before the first discovery of the pest, where $\frac{\partial E_b}{\partial t} \geq 0$, and $\gamma = \left(\frac{t}{n}\right)\left(\frac{\partial n}{\partial t}\right) \leq 0$, is the time elasticity of the conditional probability of discovering the pest. Eq. (3) states that the probability of discovering a forest pest at time t, and the conditional probability of discovering a pest during the next year, declines as the adoption of preventive measures increases.

Eq. (3) can be rewritten as the state equation:

$$\frac{\partial N(t)}{\partial t} = n(E_b(t))[1 - N(t)], \;\; n(E_b(t=0)) = 0, \;\; \frac{\partial n}{\partial E_b} < 0; \tag{4}$$

where $\frac{\partial N(t)}{\partial t}$ is the probability density function of the time for initial discovery of a pest.

Once a pest is discovered in a tract of forest, landowners can implement control measures, (i.e., $E_a(t)$), to reduce the associated damages (e.g., more aggressive spraying and removal of infected and nearby trees). Populations of pest species are assumed to follow a logistic growth function (Eiswerth and Johnson, 2002; Huffaker and Cooper, 1995). When control measures are implemented, we adjust the population growth function to (Kim et al., 2007):

$$\frac{\partial a(t)}{\partial t} = g[1 - k(E_a(t))]a(t)\left[1 - \frac{(1 + k(E_a(t)))a(t)}{A}\right], \tag{5}$$

where a is acres impacted by the pest in time t, A is total acres, g is the rate of tree pest spread, and E_a is control measures after discovery of tree pests such that $\frac{\partial k}{\partial E_a(t)} > 0$, where k is a fractional coefficient reflecting the technical effectiveness of the control measures.

Traditionally, forest product models have employed timber growth functions that are based on the age-structure of the trees in the forest area of interest (Amacher et al., 2005, 2009; Chang, 1984; van Kooten et al., 1995). The logic being that trees grow at relatively predictable rates so if one knows the species mix and age-structure of the trees in a given tract, one can assess with reasonable accuracy the volume of timber — and sequestered carbon — in the tract at any point time. Age-structured growth models are particularly suited to afforestation where forest is established on land previously in a less carbon intense use — typically cropland or grass. This means that the species mix will be known and all trees will be of the same age. An alternative approach would be to use a size-structured growth

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[1] Previous studies in forest management considered either fire hazards (Amacher et al., 2005; Johnson and Wagner, 1985) or pest hazard (Kim et al., 2007), but not both fire and pest hazards simultaneously.