Incentives for Carbon Sequestration Using Forest Management

Abstract

This research uses an econometric model to analyze the factors affecting non-industrial private forest landowners' choice of intermediate forest management practices, and to examine how these choices might change in response to incentives for carbon sequestration. We also use parameter estimates to simulate the carbon sequestration potential for different combinations of management practices, and compare the effectiveness and costs of carbon sequestration-based and practice-based incentive payment schemes. Our results suggest that incentive payments increase the probability that desirable combinations of management practices are adopted. Simulation results indicate that incentives targeting fertilization yield the highest carbon sequestration potential, and that a carbon-based payment scheme produces higher carbon sequestration than a practice-based payments scheme.

Key Words: Carbon Sequestration, Incentive Payments, Fertilization, Fuel Treatment, Intermediate Forest Management, Incentive Payments.

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I. Introduction

There is widespread recognition of the potential role forests can play in contributing to Greenhouse Gas (GHG) reductions through carbon sequestration (Lubowski et al. 2006). Over half of the forest land in the U.S. is owned by private entities, and most private forests are held by nonindustrial private forest owners (NIPFs).[1] Thus, it is important to assess the role that NIPF landowners can play in broader carbon sequestration efforts. The NIPF category comprises individuals, families, or private groups that own forest land but do not own or operate primary wood-processing facilities. Here we focus on family forest owners, who constitute the majority (92%) of private forest owners, and own 62% of private forest land area and 35% of all forest land (Butler 2008).

It is well established that providing incentives for landowners to sequester carbon in forests is a comparatively low-cost option relative to energy-based GHG mitigation approaches (Lubowski et al. 2006; Mason and Plantinga 2011). Existing studies of landowners' response to carbon sequestration incentives have largely focused on afforestation and reforestation (Adams et al. 1993; Parks and Hardie 1995; Alig et al. 1997; Plantinga et al. 1999; Stavins 1999; Lubowski et al. 2006). However, longer rotations, choosing alternative tree species, and intermediate forest management can potentially increase carbon sequestration as well (Stainback and Alavalapati 2002; Shaikh et al. 2007).[2] For instance, Row (1996) shows that changes in forest management can increase sequestration by 0.6-0.8 metric tons (Mt) of carbon per acre per year. The IPCC (2000) shows that regeneration, fertilization, choice of species, and reduced forest degradation can sequester around 0.2 Mt per acre per year. North et al. (2009) conclude that thinning and prescribed burning allow greater long-term storage of carbon.

Only a handful of studies have examined the potential for using incentives such as taxes, carbon payments, or other subsidies to increase carbon sequestration through changes in forest management (Plantinga and Birdsey 1993; Englin and Callaway 1993; Sohngen and Brown 2008). One important drawback of these studies is that most of them analyze the sequestration effects of individual forest management activities independently, while in practice these activities may be conducted jointly. In addition, most of these studies focus on rotation length or harvest decisions, while few examine other activities such as fertilization or thinning. Consequently, we know less about the efficacy and cost effectiveness of incentives to elicit additional carbon sequestration in existing forests through intermediate forest management practices than we know about afforestation or other management practices. We also lack a clear empirical understanding of the factors driving forest owners' decisions regarding intermediate management practices, as there are only a relatively small number of econometric studies on timber stand improvement (Beach et al. 2005).

In this study we use data from the National Woodland Owner Survey to estimate an econometric model of the choice of intermediate forest management practices and identify the factors affecting NIPF owners' choices. We use estimation results to examine how these choices might change in response to incentives for carbon sequestration. Additionally, we simulate the carbon sequestration potential for different management practices and compare the effectiveness and costs of carbon sequestration-based and practice-based incentive payment schemes.

Thus, this paper makes four important contributions to the literature. First, the empirical model of landowner behavior improves our understanding of how returns to different management actions and other factors, such as landowner attributes and land characteristics, affect management choices. We also provide insight into how this information could be used to improve policy, for instance by identifying traits of landowners that may make them more likely to adopt desirable management options if provided with incentives. Second, our empirical results allow us to simulate the effect of incentives on adoption of different management options, and thus to estimate the potential carbon sequestration effect of such incentives. This provides insight into the relative efficacy and cost effectiveness of carbon sequestration resulting from intermediate forest management, including management options not usually analyzed in the literature, such as fertilization and thinning. Third, our results highlight an important potential tradeoff in forest management between fire risk reduction and carbon sequestration. Our simulations suggest that thinning, a common management tool to reduce fire risk, may provide smaller carbon sequestration benefits than fertilization or even than no management. This could have important policy implications when considering multiple objectives of forest management. Finally, in this paper we extend the comparison of two alternative incentive payment criteria, practice-based and carbon (performance)-based contracts, which previously had been carried out in the context of soil carbon sequestration, to the forest carbon sequestration context.

Our analysis and results also highlight the need for further research on forest management as an alternative for carbon sequestration. For instance, an analysis of forest owners in other regions of the US would indicate whether our findings apply more broadly than to Western landowners. Similarly, additional intermediate forest management options or alternative incentives could be examined. Finally, a broader consideration of the effects of management choices on other policy objectives, such as fire risk or biodiversity, would provide a more complete picture of the desirability of promoting intermediate forest management options through the use of incentives.

The remainder of this article is organized as follows. Section 2 presents the conceptual background and model specification, section 3 describes the data used to estimate the empirical model and conduct simulations. Section 4 presents the results of the econometric model. In section 5 we discuss baseline carbon sequestration potentials, the incentive payment design, and the simulation of carbon sequestration potentials with different incentive payment strategies. Section 6 discusses sensitivity analysis. Section 7 includes a discussion of the main findings and the conclusion.

II. Conceptual Background and Model Specification

In this section we describe the conceptual background underlying NIPF landowners' forest management choices and the corresponding empirical model specification. It is well established that NIPFs jointly produce timber and non-timber amenities provided by their forest, and hence their management decisions are commonly modeled using a utility maximization framework (Binkley 1981; Hyberg and Holtahusen 1989; Dennis 1990; Kuuluvainen et al. 1996; Pattanayak et al. 2002).[3] In our sample, 84% of landowners have an occupation that is unrelated to farming, logging, or the timber industry, which suggests that a utility maximizing framework may be appropriate to model their management decisions. We verify the robustness of our estimation results to excluding the remaining 16% of landowners in section 6.

Consider a utility-maximizing NIPF owner who can choose among K different management practices, with $k = 0$ indicating no management. The NIPF owner maximizes expected utility from managing forestlands: practice k will be chosen if $U_k > U_j$ for all $k \neq j$, where U_k is the utility of adopting practice k. Because the landowner's utility is a function of both observable and unobservable components, the landowner's management choice problem can be modeled using a general random utility approach. Let $U_{ik}(Z_{ik})$ be the expected utility of landowner i from choosing management practice k on her forestland, with $Z_{ik} = [X_{ik}, W_i]$. The vector X_{ik} includes attributes of forest management choices that vary across choices and across individual landowners, such as expected net returns. The vector W_i includes characteristics of individual landowners and of their land which vary only over landowners (Greene 2008).

By considering both observable and unobservable components of the management decision, $U_{ik}(Z_{ik})$ can be considered a random variable and written as:

$$U_{ik}(Z_{ik}) = Z_{ik}^{'}\beta_k + \varepsilon_{ik} \tag{1}$$

where β_k is a vector of parameters and ε_{ik} is a random error term. The probability that NIPF owner i will choose management practice k is:

$$\Pr(y_i = k) = \Pr(U_{ik} \geq U_{ij}) = \Pr(Z_{ik}^{'}\beta_k + \varepsilon_{ik} \geq Z_{ij}^{'}\beta_j + \varepsilon_{ij}) \ \forall k \neq j \tag{2}$$

Hence the choice depends on both attributes of the management practices, such as net returns, and on individual landowner and parcel characteristics, such as age or reasons for owning forest land, that may affect landowners' preferences for the various management options. We assume the error term ε_{ik} is independently and identically distributed with the extreme value distribution, and specify the probability that NIPF owner i will adopt management practice k using a multinomial logit model (MNL) (McFadden 1974):

$$\Pr(y_i = k) = \frac{e^{Z_{ik}^{'}\beta_k}}{\sum_{j=0}^{K-1} e^{Z_{ij}^{'}\beta_j}}, \ k = 0,1,2,...,K-1 \tag{3}$$

In the following section we describe the data used to estimate this model.

III. Data

We use data from the National Woodland Owner Survey (NWOS) conducted by the US Forest Service. Roughly 6,000 randomly selected private forest owners from across the U.S. are asked to participate every year. These owners are chosen on the basis of an area-based systematic random sampling design. Data are collected on woodland owners' forest management behavior, landowners' attributes, and land characteristics.[4] The spatial location of individual plots is also provided,[5] which allows us to incorporate stand information for each forestland from the Forest Inventory and Analysis (FIA) constructed by the US Forest Service. We use data from the Western United States (Arizona, Colorado, California, Idaho, Montana, New Mexico, Oregon, Utah, Washington, and Wyoming). There are a total of 593 observations covering the years 2002 - 2006. Of these, 513 observations are defined as family forest owners.

We use the forest management section of the NWOS data to construct the dependent variable in our model. The available management activities are thinning (partial harvest to improve the growth of remaining trees), fire hazard reduction (thinning to remove ladder fuels, pruning, prescribed underburning), and fertilization (direct application of nitrogen or urea to increase forest productivity). Most landowners who adopt thinning also conduct fire hazard reduction, and thinning is commonly considered as an activity to control fire hazard. Hence, we combine thinning and fire hazard control into a single management practice, fuel treatment. Thus, the independent variable in our model is landowner *i*'s choice of intermediate forest management practice: fertilization and fuel treatment, fertilization only, fuel treatment only, or no management activities.[6]

A set of key explanatory variables in our model are the owner-specific expected net returns for the different choices of management practices. Data on expected net returns are not available, so we construct a measure of annual net returns using the annualized value of land and timber stands (LTV) (Latta and Montgomery 2004). The LTV for each management choice *k* and landowner *i*, based on the current stand volume, is

$$LTV_{ik} = \frac{\sum_{t=t^0}^{T} (P_{ikt}Q_{ikt} - C_{ikt})(1+r)^{T-t} + SEV_{ik}}{(1+r)^{T-t^0}}, \quad \text{s.t. } T - t^0 \leq \omega \tag{4}$$

where T is the final harvest year,[7] t^0 is the current year, P_{ikt} is stumpage price, Q_{ikt} is the per acre harvest volume, and C_{ikt} is the per acre cost of stand treatments applied for i and k at year t, ω is the maximum range of the time horizon, r is the annual discount rate, and SEV_{ik} is the value of bare land for i and k, which we assume to be the present value of timber production.[8] We annualize the LTV using a 5% discount rate over a 100-year time horizon.[9]

Owner-specific management costs (C_{ikt}) for fuel treatment are calculated by using the fuel reduction cost simulator (FRCS), which estimates the cost of fuel reduction activities by considering stand volumes and each forestland's spatial characteristics, such as distance to the closest main road, average slope, and elevation (Fight et al. 2006). We use the average price of urea fertilizer ($0.12/lb-$0.16/lb in 2003-2006) (USDA ERS 2013), fertilizer application costs including handling and spreading ($0.072/lb) (Dickens et al. 2005), and delivery expenses from the nearest main road to the plot ($0.36/mile-$0.45/mile in 2003-2006) based on the standard mileage rates of business vehicles (IRS 2013) to calculate fertilization costs.[10] Fertilizer price and application costs are not spatially explicit, but delivery costs vary according to parcel location. All prices and costs are expressed in 2006 dollars. The site specific stand volume (Q_{ikt}) for the different management combinations is calculated using the Forest Vegetation Simulator (FVS).[11,12] Location information (longitude and latitude) of each forestland plot allows us to incorporate forest inventory data (tree species, stand age, slope, elevation, aspect, basal area, diameter, height, stand volume, and number of stands), which is necessary to run the FVS.

We follow existing literature on forest management and program participation to select the remaining explanatory variables to include in our econometric model. Owner-specific variables include landowners' characteristics and parcel attributes (Ervin and Ervin 1982; Dennis 1989; 1990; Nagubadi et al. 1996; Zhang and Pearse 1996; Latta and Montgomery 2004; Beach et al. 2005; Langpap 2006; Fight et al. 2006; Zhou and Kockelmen 2008). Landowners' demographic information provided by NWOS includes age, level of education, level of household income, and occupation. Additional landowner attributes include their objectives for owning forestland, their recent concerns (future development, air quality, insects and tree disease, and risk of fire), whether they live within a mile of their forest land, whether they are a main decision maker in managing their land, previous enrollment in or knowledge of cost-sharing or green certification programs, recent harvest of non-timber products, and land acquisition method.

Parcel attributes obtained from NWOS include the size of forestlands owned and region (Pacific Northwest, Pacific Southwest, Southern Rocky Mountain, and Northern Rocky Mountain). We overlap the location information of each parcel with spatially explicit data from the Forest Inventory Analysis and the US Geological Survey to construct variables describing additional characteristics: stand density index[13], slope, distance from site to the main road, number of mills within 50 miles from the site, and the major types of tree species present in a parcel (pine, other softwoods, hard-hard woods, soft-hard woods). Finally, we include dummy variables for survey years (2003, 2004, or 2006) to account for variation in management practices over time. Table 1 presents descriptions and summary statistics for all variables used in the econometric model.

IV. Econometric Analysis

Landowner *i*'s utility from management practice choice *k* is specified as follows:

$$U_{ik} = Z_{ik}{}'\beta_k = \beta_{k0} + \beta_{k1} LTV_{ik} + \beta_{k2} Owner\ Demographic_{ik} + \beta_{k3} Forestland_{ik} + \beta_{k4} Owner\ Attributes_{ik} + \varepsilon_{ik}, \quad (5)$$

k = {no management, fertilization only, fuel treatment only, fertilization and fuel treatment}, where LTV_{ik} is a vector of annual LTVs, $Owner\ Demographic_{ik}$ is a vector of landowners' demographic characteristics, $Forestland_{ik}$ is a vector of forestland characteristics, $Owner\ Attributes_{ik}$ is a vector of landowners' attributes, ε_{ik} is a random error term for landowner i and management practice choice k, and the β_ks are parameters to be estimated with the MNL model in equation (3).

Underlying the MNL model is the Independence from Irrelevant Alternatives assumption (IIA). In this case, IIA implies that the odds ratios of any two forest management alternatives are independent of other available options. For instance, this assumes that the relative probabilities of choosing fertilization and fuel treatment over fuel treatment only remain the same, regardless of whether the option of choosing fertilization only is available or not. This might be a reasonable assumption if landowners do not consider either fertilization or fuel treatment by themselves as a good substitute for their combined application, since the two activities are not good substitutes for each other. Additionally, neither of these choices is a close substitute for not carrying out any management activities, which is the remaining option.

We conducted a modified Hausman-McFadden test of the IIA assumption (Long and Freese 2006). The p – values for the test statistic range from 0.104 to 1.0 (the chi-square statistic for 80 degrees of freedom ranges from 23.9 to 96.3), depending on which alternative is omitted. This suggests that we cannot reject the null hypothesis that the odd ratios are independent of other alternatives. We also conduct sensitivity analysis using a model specification that relaxes the IIA assumption. Results are discussed in section 6.

We use the estimated parameters to identify the determinants of NIPF owners' choices of management practice combinations. This contributes to a better understanding of which landowner and parcel characteristics drive intermediate silvicultural management decisions and of the behavior of this set of forest landowners. Since the interpretation of coefficients in a multinomial logit model is difficult, we use marginal effects to examine the different factors that affect NIPF owners' choices.[14] Table 2 shows the marginal effects of the explanatory variables, calculated using the model coefficients and the sample means of the variables. The estimated coefficients are included in Table A1 in the appendix.

As expected, the own marginal effects with respect to LTVs are all positive and significant, which confirms that an increase in the LTV for a forest management practice will increase the likelihood that the practice is chosen. To get a better idea of the magnitude of these effects, we calculated semi-elasticities of the probability of choosing the different management combinations with respect to annual LTVs.[15] The semi-elasticities indicate that a 1% increase in the LTV of a management option increases the probability of adopting fertilization and fuel treatment by 0.20 percentage points, fertilization only by 0.28 percentage points, fuel treatment only by 0.7 percentage points, and no management by 0.41 percentage points. These results agree with previous findings that NIPF landowners are not very responsive to market signals, possibly due to the opposing influences of income and substitution effects (Dennis 1989; Beach et al. 2005).

The cross marginal effects with respect to annual LTVs have mostly negative signs, although not all are significant. For example, a higher annual LTV for fertilization and fuel treatment decreases the probability of choosing fertilization only and fuel treatment only. Similarly, a higher annual LTV for fuel treatment decreases the probability of choosing other combinations.

The marginal effects of the income variables suggest that landowners with income below $50,000 are less likely to choose fertilization only than landowners with income between $50,000 and $100,000 (the base category). Additionally, landowners in all included income categories are more likely to choose fuel treatment only than landowners with income between $50,000 and $100,000. On the other hand, except for landowners without a high school education or with a graduate degree being more likely to choose no management than landowners with only a high school education, the indicator variables for education level do not have a statistically significant impact on management decisions. This lack of significance could be due to collinearity between income and education. Furthermore, these variables may also be to some degree collinear with other regressors, such as objectives for forest ownership, which reflect the relative values placed by landowners on amenities and income provided by their forests (Dennis 1989). We explore the robustness of our results to excluding these sets of variables in section 6.

Landowners with occupations related to farming, logging, or the timber industry are less likely to choose fertilization only, and more likely to choose fuel treatment only. One possible explanation is that these landowners may be more likely to view their forest as an income-producing asset, and thus are more likely to choose management activities that increase the commercial value of their forest. Finally, age of the landowner does not have a statistically significant impact on management choices. This agrees with previous findings in Dennis (1989) and Langpap (2006).

Table 2 indicates that some of the parcel characteristics have an impact on management choices. Landowners who own properties with low slope are more likely to choose fuel treatment only and less likely to choose no management. This is consistent with the notion that higher site quality (a lower slope) renders silvicultural investment more attractive and thus increases the amount of silvicultural activity (Zhang and Pearse 1996; Beach et al. 2005). Additionally, landowners who own parcels that are located closer to roads are more likely to choose fuel treatment only and less likely to choose fertilization only or no management. This is consistent with the fact that smaller distance to a main road reduces forest management costs, which may induce more intermediate management or harvesting (Latta and Montgomery 2004; Fight et al. 2006; Zhou and Kockelmen 2008). Forest acreage owned, stand density, and number of mills within fifty miles do not have a statistically significant effect on management choices.

Other landowner attributes also have an effect on management choices. Forest owners with forestry expertise or previous experience with certification programs are more likely to choose fuel treatment only and less likely to choose no management. This may be because landowners with this kind of expertise or experience are more knowledgeable about intermediate management and more interested in managing for commercial purposes, and hence more apt to actively manage their forest. Owners whose residence is located within a mile from their forestland are more likely to choose fertilization only or fuel treatment only and less likely to choose no management. One potential reason is that proximity to forestland facilitates access to the property as well as implementation and oversight of silvicultural management activities (Nagubadi et al. 1996). Additionally, landowners who have previously participated in cost share programs are more likely to choose fertilization and fuel treatment, and less likely to choose fuel treatment only. This could be because familiarity with policies that lower the cost of forest management tends to increase the intensity of forest management activities, and is consistent with existing evidence that NIPF landowners are more likely to respond to targeted government programs (such as cost sharing) than to other factors, including market price (Beach et al. 2005).

Finally, landowners who recently harvested non-timber products are more likely to choose fertilization only and less likely to choose no management, perhaps because these landowners have a preference for management that does not involve thinning and selective harvesting for fuel treatment.

Landowners' ownership objectives also have an impact on management decisions. Landowners who own forestland to harvest timber are more likely to choose fuel treatment only and less likely to choose no management. This could be because these landowners prefer management activities that increase the commercial value of their forest. Landowners for whom privacy is an ownership objective are less likely to choose fuel treatment and fertilization or fuel treatment only, and more likely to choose no management. This result probably reflects the landowners' lower interest in active management, particularly the thinning involved in fuel treatment. Landowners who own their forest for recreation purposes are (marginally) more likely to choose fertilization only, possibly because they may be more interested in thicker forest stands. Landowners who own forest for biodiversity conservation purposes are more likely to choose fuel treatment only and less likely to choose fertilization only. This may be because fuel treatment involves more active thinning, which promotes growth of understory vegetation and habitat breadth, thereby increasing biodiversity (Verschuyl et al. 2010).

Finally, landowners' expressed concerns also affect their management choices. Landowners who are concerned about fire are, understandably, less likely to choose no managment or fertilization only and more likely to choose fuel treatment only. Landowners with concerns about disease of their trees are more likely to choose fertilization only, perhaps because this management option is considered as a better defense against the possibility of disease. Landowners who are concerned about land development may be those that manage their forests more actively, and hence are more likely to choose fuel treatment and fertilization and less likely to choose fertilization only.

These results have important policy implications. A better understanding of the drivers of landowners' management decisions can help policy makers identify and target groups of landowners who may be less likely to adopt desirable management options in the absence of incentives such as the ones examined in the following section. For instance, our estimates indicate that landowners whose primary occupation is related to logging, whose management decisions rely on foresters or logging contractors, who own land for timber production purposes, or whose land has characteristics that favor timber production (such as low slope and proximity to roads) are more likely to choose fuel treatment only. This suggests that if policy makers wanted to increase adoption of fertilization they would want to offer incentives to landowners who can be identified as more likely to be timber producers, since they would be less likely to adopt this management option otherwise. Similarly, our estimates indicate that landowners who are concerned about fire are less likely to choose fertilization only. Hence, policy makers could promote adoption of this management option by implementing policies that directly decrease the risk of fire or by educating landowners about fire risk and its management. These examples indicate that knowledge of the factors driving landowners' management decisions can be valuable for the design and targeting of policy aimed at encouraging adoption of desired management options.

We use the estimated parameters from the econometric model and the data to generate predicted choice probabilities for each management option. Then we predict each landowner's management choice as the option with the highest predicted probability for that landowner. The model predicts landowners' choices well: 68% of actual choices are predicted as the first choice by the model, and 92% of actual choices are predicted as the first or second choice by the model. Based on the predicted choices, 5.8% of landowners will choose fertilization and fuel treatment, 4.5% choose fertilization only, 37.2% choose fuel treatment only, and 52.4% choose no management. Since each landowner owns forestland of different size, we also calculate predicted probabilities of management choices weighted by acreage: 11.9% of forest acres are managed with fertilization and fuel treatment, 5.9% with fertilization only, 43.7% with fuel treatment only, and 38.5% with no management.[16] These predicted choices allow us to calculate baseline carbon sequestration potentials in the following section. Then we simulate the effect of incentives on adoption of management choices and the corresponding changes in amount of carbon sequestered.

V. Incentive Payments for Carbon Sequestration

In this section we examine the potential effects of incentives to increase carbon sequestration.

Carbon sequestration baseline and trends

We start by assessing carbon sequestration potentials for each management practice to identify which activities to target with incentive payments. We use the estimates from the econometric model and the FVS to simulate carbon accumulation trends after each of the different management options have been implemented. Specifically, for each option (no management, fertilization only, fuel treatment only, fertilization and fuel treatment) we assume that all landowners choose only that option.[17] We account for the timing of sequestration and discount the corresponding costs using the discounting method outlined in Richards and Stokes (2004) and Stavins and Richards (2005). Figure 1 shows the average carbon accumulation trend of each individual management practice when trees are allowed to grow without harvest for 100 years.[18]

The carbon accumulation trends show that fertilization has the highest carbon sequestration potential. It is important to note that we only consider the impact of fertilization on sequestration through its effect on increased biomass. Another potential impact of fertilization is through emissions of N_2O. In contrast to agriculture, however, fertilization in forestry likely has limited effects on greenhouse gas (GHG) emissions. Pang and Cho (1984) show that nitrogen fertilization is a negligible source of emissions from forest soils. Van Migroet and Jandl (2007) show that the effect of nitrogen fertilization on above-ground biomass is large enough to offset soil carbon loss. Similarly, Jassal et al. (2008) find a net decrease in GHG global warming potential from nitrogen fertilization despite N_2O emissions, and Jassal et al. (2010) find increases in net carbon sequestration due to nitrogen fertilization, except for very young stands. Finally, the production and transportation of fertilizer also generates GHG emissions, which are not accounted for in our analysis. For example, Scott and Perry (2008) document emissions of 0.09 tonnes of carbon equivalent per acre from manufacture and 0.003 tonnes of carbon equivalent from transportation and application of fertilizer. However, the available evidence suggests that emissions from production and transportation are low relative to the additional sequestration generated by fertilization (Scott and Perry 2008; Albaugh et al. 2012).

The next highest carbon sequestration potential is for the no management option, which is always greater than that of fuel treatment and of fertilization and fuel treatment combined. This implies that removing some portion of trees by thinning to enhance the quality of remaining trees and fire resistance does not provide higher total carbon benefits than the choice of no thinning. One important caveat is that the carbon accumulation trends shown in Figure 1 do not incorporate the potential effects of fire. However, while accounting for fire risk may reduce the difference in carbon sequestration between thinned and unthinned stands and hence lower the carbon sequestration potential of switching management practices, this result is consistent with recent findings on the tradeoffs between carbon sequestration and fire risk reduction. For example, McKinley et al. (2011) argue that, while thinning reduces fire risk, the carbon stock in a thinned stand is generally lower than in an unthinned stand. Similarly, Law and Harmon (2011) and Campbell et al. (2012) make the point that the amount of biomass reduction required to achieve significant reductions in fire severity would result in a net emission of CO_2, because the amount of carbon loss caused by thinning is larger than the carbon loss avoided by reducing the possibility of fire. Hence, they conclude that even if the risk of fire is considered the carbon sequestration potential with fuel treatment is lower than with no management.

Given the carbon sequestration trend of each management choice, we calculate the baseline carbon sequestration trend per acre, which is the average annual carbon accumulation of the different management practices weighted by the corresponding predicted probabilities of management choices.[19] We assume that the predicted proportion of management practices will not change over time if other conditions facing landowners remain the same.

Incentive payments

We assume that the goal of the incentive payments program is to increase carbon sequestration by encouraging NIPF owners to switch their current management to alternative practices. We use simulations to examine how the adoption rate of each management practice will change with different levels of incentive payments and measure how much additional carbon can be sequestered with this change in adoption rate. The carbon sequestration trends shown in Figure 1 suggest that (without considering the risk of fire) an increase in the adoption of fuel treatment only does not increase, and may even reduce, the annual carbon sequestration rate, while an increase in the adoption of no management or fertilization only can increase the carbon sequestration rate. Since the goal of the incentive payments is to produce additional carbon sequestration, we focus on incentive payments targeted to increase the likelihood that no management and fertilization are chosen.[20] Hence, the possible combinations of incentive payment targets can be classified as follows: i) Provide incentives for fertilization only, so only landowners who adopt the fertilization choice receive payments and those who implement other activities are not eligible; ii) Pay for fertilization no matter what other combined activities are, so landowners who choose fertilization and fuel treatment or fertilization only receive payment; iii) Pay only for no management, so only landowners who make this choice receive payment; and iv) Pay for no management or for fertilization only, so landowners who adopt fuel treatment are not eligible.

The effects of incentive payments to encourage adoption of specific management practices are simulated by changing the level of annual LTV for that particular practice choice. An incentive payment to adopt forest management choice *k* increases the annual LTV of that management practice and therefore modifies the estimated adoption probabilities P_k as follows (Lubowski et al. 2006):

$$P_{ik} = f(\hat{\beta}_k, LTV_{ik} + Payment_{ik}, LTV_{ij}, Owner\ Demographic_i, Forestland_i, Owner\ Attributes_i) \quad (6)$$

where $Payment_{ik}$ is the annual payment per acre for carbon sequestration. We then calculate the impact of the incentive on carbon sequestration based on the net increment in the adoption rate of a given management practice relative to the baseline.

We assume that the landowner and an agency providing the incentive enter into a contract specifying the agreed-upon activity and the amount of the payment. The duration of the contract is ten years (we check the robustness of our results to alternative contract lengths below).[21] We assume that no harvesting is allowed during the length of the contract to ensure there is enough time for sequestration to take place, but harvesting takes place after ten years. This is necessary because there is a time lag between switching management practices and achieving a given level of sequestration. The incentive payments we use in the simulations range from $0 to $150 per acre for the duration of contract, rising in $10 increments.[22] Within the duration of a contract, payments decrease over time as predicted carbon sequestration rates decline. When measuring the additional sequestration induced by the incentive payment and the induced switch in management practice, we only consider the amount of carbon sequestered within the duration of the contract.[23] We annualize the amount of carbon sequestration over a hundred year time horizon using a 5% rate.

An important aspect of the incentive contract is the payment criterion. We consider two criteria: i) a practice-based contract in which the goal of incentive payments is to change the management practice itself, and ii) a carbon-based contract in which the goal is to change the environmental benefits, i.e. the amount of carbon sequestration, through the change of management practice. Antle et al. (2003) find that carbon-based contracts achieve greater benefits in soil carbon sequestration than practice-based contracts. However, existing environmental programs such as the Conservation Reserve Program (CRP), the Environmental Quality Incentive Program (EQIP), and the Wetland Reserve Program (WRP) have offered payments to support voluntary changes in management practices rather than to directly support the production of environmental benefits by taking into account the spatial variability of ecosystems. We use our simulation framework to compare the additional carbon sequestration achieved by these two payment criteria.

Finally, we use the simulation results to derive a supply function for carbon sequestration based on the annualized carbon price (the incentive payment in $/Mt) and the corresponding annualized amount of carbon sequestration. Since this study focuses on NIPF landowners in the western US, we derive the supply function for this region by defining 42 million acres (62%) out of 68 million acres of total private forest lands in the region as NIPFs.

Carbon Sequestration Potential under Practice-Based and Carbon-Based Payments

Under a practice-based payment criterion, we assume that NIPF landowners are offered incentive payments to change their current management to practices that might lead to increased carbon sequestration. Landowners receive a uniform per-acre incentive payment, and the total payment received is based on the acreage of lands enrolled in the program. We carry out simulations for each of the four possible incentive payment targets: fertilization only, fertilization only or fertilization and fuel treatment, no management, and fertilization only or no management. The results are presented in Table 3. The table shows that the annual carbon sequestration potential increases with the amount of incentive payment for fertilization only (ranging from 1.14 million metric ton (MMt) to 5.86 MMt), no management (1.05 MMt to 3.44 MMt), and the combination fertilization only or no management (1.29 MMt to 3.98 MMt). For the combination fertilization only or fertilization and fuel treatment the sequestration potential initially increases, but then decreases with the incentive payment (from 0.58 MMt to 1.14 MMt and then to 0.09 MMt). This is because as the incentive payment goes up a higher proportion of landowners choose fertilization and fuel treatment, crowding out those choosing no management, which has a larger carbon sequestration potential than fertilization and fuel treatment.[24] This suggests that a payment for fertilization without restricting the choice of fuel treatment may reduce the carbon sequestration potential as the payment level increases.

Figure 2a shows the corresponding carbon supply function (marginal cost curve) for the western US with respect to the annualized carbon prices ($/Mt) for a practice-based payment criterion. Targeting fertilization only or no management produces the highest carbon sequestration potential for prices less than $91/Mt, while targeting fertilization only yields the highest annual carbon sequestration at carbon prices above $91/Mt. The maximum available amount of annual carbon sequestration is 5.9 MMt at a price of $215/Mt.

Under a carbon-based criterion NIPF landowners are also offered a per-acre incentive payment, but the payment rate varies across landowners based on the annual carbon sequestration per acre (over the duration of the contract) resulting from adoption of specific management practices. We calculate carbon sequestration per acre using the FVS. Table 3 shows the corresponding simulation results for each of the four incentive payment targets. The annual carbon sequestration potential increases with the incentive payment for all four management practices, ranging from 1.75 MMt to 6.04 MMt for fertilization only, from 1 MMt to 2.1 MMt for fertilization only or fertilization and fuel treatment, from 1.62 MMt to 3.44 MMt for no management, and from 2.32 MMt to 5.92 MMt for fertilization only or no management.

Figure 2b shows the corresponding carbon supply function for the western US. Targeting the management options fertilization only and fertilization or no management yields the highest annual carbon sequestration. For the combination of fertilization only or fertilization and fuel treatment, the supply of carbon stops increasing and begins to decline slightly as the payment increases beyond roughly $245/Mt. This is because at higher payment levels landowners begin switching from no management to fertilization and fuel treatment, which reduces the amount of carbon sequestration. At the same time, the amount of carbon gained from increased adoption of fertilization only is very close to the amount of carbon lost from increased adoption of fertilization and fuel treatment.

We use the preceding results to compare the carbon sequestration potential of a practice-based payment scheme and a carbon-based payment scheme. Figure 3 shows the annual carbon sequestration potential in the western US for each of the four different management targets under each of the two payment schemes. The carbon-based payment scheme yields higher levels of carbon sequestration than the practice-based payment scheme in almost every instance, particularly at lower annual payment levels.[25] This is because the lands with higher carbon sequestration potential are paid more under the carbon-based payment scheme.[26] This implies that paying incentives directly to support carbon sequestration by taking into account spatial variability performs better than supporting acreage enrollment of a certain management practice.

VI. Sensitivity Analysis

Independence from Irrelevant Alternatives Assumption (*IIA*)

We check the robustness of our estimation results to relaxing the IIA assumption inherent in the multinomial logit model by estimating a multinomial probit model. The multinomial probit relaxes the independence assumption built into the MNL by allowing an unrestricted correlation structure for the disturbances in the model (Greene 2008). The results are very similar to those reported for the MNL, suggesting that the IIA assumption is not unduly restrictive in our data.

Alternative Model Specifications

We also checked for robustness of our estimates to alternative model specifications. We estimated a version of the management choice model that excludes the landowners who have an occupation related to farming, logging, or the timber industry. The corresponding marginal effects are reported in Table 4. We also estimated models that exclude income indicator variables or exclude education indicator variables. Finally, we estimated a model that includes a gender indicator variable, as well as a count variable for the number of unconnected parcels owned by a landowner, but these variables are not statistically significant. The results for all these alternative specifications are consistent with those reported in table 2.

Discount Rates

In the econometric and simulation analysis we use a 5% discount rate to calculate annualized net returns (annual LTV) and incentive payments. We examine the sensitivity of the predicted probability of the different management choices and of carbon sequestration to lower (3%) and higher (7%) discount rates. As the discount rate rises from 3% to 5% and 7%, the annual LTV of each management practice becomes lower. In the econometric analysis, as the discount rate becomes higher the relative magnitude of own marginal effects of fertilization and fuel treatment and fuel treatment increase relative to other management practices. This implies that as the discount rate changes from low to high, the probability of choosing management options which allow partial harvest become more responsive to changes in returns. An increase in the discount rate also changes the predicted probabilities of adoption for the different management practices. In particular, as the discount rate increases the predicted probability of adopting the choices including fuel treatment (fertilization and fuel treatment and fuel treatment only) goes up. This implies that a higher discount rate increases partial harvest (i.e. thinning as a type of fuel treatment). As a result, the baseline carbon accumulation declines as well.

The effect of an increasing discount rate on the carbon sequestration potential is ambiguous. As the discount rate goes up, the level of annualized payments increases as well. However, the responsiveness to annual returns also changes with the discount rate, so the net effect is ambiguous. We illustrate possible effects in Table 5, which shows the annual carbon sequestration potentials at a carbon price of $80/Mt when the discount rate increases from 3% to 5% and 7%. Annual carbon sequestration rises with the discount rate for choices fertilization only, fuel treatment and fertilization or fertilization only, and fertilization only or no management under both types of payment schemes. However, in the case of payments targeting the choice no management, annual carbon sequestration decreases as the discount rate goes up. This is because the responsiveness of the adoption probability of no management to annual payments decreases considerably when the discount rate goes up. This leads to a lower adoption rate of the choice no management at a discount rate of 7%, even if the payment level at 7% is relatively high. However, the result that management practices fertilization only and fertilization or no management yield higher sequestration, and that carbon-based payments yield higher carbon sequestration potential than a practice-based scheme are robust to changes in the discount rate, which is the same across the carbon prices.

Contract Duration

We also conducted simulations with alternative contract durations of 5 and 15 years to examine how carbon sequestration potentials and prices of carbon differ with contract duration. As the duration of the contract increases, the annual payment level per acre goes up as well. This induces an increase in the adoption rate of management practices that boost carbon sequestration, and thus increases annual carbon sequestration potential. However, since the annual carbon sequestration rate is decreasing over time, the impact of an increase in the duration of the contract on the cost per unit of carbon under different incentive payment targets and criteria is ambiguous. In particular, note that if incentive payments rise faster than annual carbon sequestration as the duration of the contract increases, the marginal cost of carbon sequestration will go up. Our simulation results suggest that as the duration of the contract increases from 5 to 10 years, the average carbon sequestration potential increases for a given level of carbon price, and hence the marginal cost decreases. When contract duration increases from 10 to 15 years, average carbon sequestration for a given price tends to decrease, and hence the marginal cost goes up.

An example is illustrated in Table 6, which shows annual carbon sequestration for the various management practices and the two payment schemes at different contract lengths at a carbon price of $80/Mt. In general, a ten-year contract yields higher levels of carbon sequestration.[27] This is because there is a time lag to achieve a given level of carbon sequestration, and thus a 5-year contract cannot produce as much carbon as a 10-year contract for a given level of annual payment. With a 15-year contract, because of the decreasing yield of annual carbon sequestration, the marginal cost to produce additional carbon sequestration is higher than with a 10-year contract. The exception to this pattern is the case of payments targeting no management, for which annual carbon sequestration potential decreases as the duration of the contract increases. This is because a large portion of additional carbon sequestration is lost by converting from other practices to no management as soon as the decision to convert is made. Nevertheless, the results in Table 6 suggest that our results are robust to the choice of contract duration. Management practices fertilization only and fertilization or no management yield higher sequestration, and more carbon is sequestered when using a carbon-based scheme than when relying on practice-based payments.

Comparison with other studies

It is relevant to ask how the carbon sequestration potential of the forest management practices analyzed here compares to other existing estimates. However, there are no comparable studies of the carbon sequestration potential of intermediate forest management practices. It is only possible to compare the carbon supply functions estimated here with supply functions from studies that estimate the cost of sequestration through afforestation. Such a comparison requires that we normalize our results by adjusting for discount rates, geographic region, and constant-year dollars, and that we scale up from a regional level to a national level supply function by applying our results to 751 million acres of forestland in the US. The results of this exercise, therefore, should be interpreted with caution, but they do provide context for our results.

Stavins and Richards (2005) summarize and compare eleven studies on carbon sequestration potential through afforestation using a normalized carbon supply function. They show that in the US the cost of carbon (after normalization to 2006 dollars) ranges from $35/Mt to $104/Mt for 272 MMt of annual carbon sequestration, and between $41/Mt and $124/Mt for 454 MMt of annual carbon sequestration.[28] In our results, the cost of carbon by targeting the options fertilization only, no management, or both ranges from $48/Mt to $227/Mt for 50 MMt of annual carbon sequestration. Only payments targeting the fertilization option can achieve 100 MMt of annual carbon sequestration at a carbon price between $169/Mt and $190/Mt. At a carbon price of $80/Mt (the average carbon price based on Stavins and Richards (2005)), annual carbon sequestration ranges from 17 MMt to 38 MMt for a practice-based payment, and from 18 MMt to $72 MMt for a carbon-based payment. This suggests that incentive payments for intermediate forest management yield less carbon at a relatively higher cost than incentives for afforestation, and hence that the carbon supply function for intermediate forest management is steeper than that for afforestation. This is shown in Figure 4, which compares the carbon supply functions for targeting the option fertilization only with those from previous afforestation studies (normalized as in Stavins and Richards (2005) and Lubowski et al. (2006)). An important implication of this is that changing only intermediate forest management practices without extending the rotation period cannot produce as much sequestration as afforestation, because the physical carbon sequestration potential per acre is lower than that with afforestation.

VII. Summary and Conclusions

It is generally agreed that the cost of carbon sequestration through afforestation is comparable to or lower than the cost of energy-based mitigation approaches. However, we know much less about the cost effectiveness of using incentives to elicit additional carbon sequestration in existing forests through intermediate forest management practices. This study takes a first step towards filling this void by analyzing the factors affecting NIPF landowners' choice of intermediate forest management practices and examining how these choices might change in response to the use of incentives for carbon sequestration. We also simulate the carbon sequestration potential for each management practice given different incentive payment schemes.

Our results suggest that the factors affecting the probabilities of adopting intermediate management practices differ by the choice of practice. We find that an increase in the expected net returns of a given practice increases the probability of adopting that practice, but the effect is small. Landowners' demographic characteristics mostly do not affect the probability of choosing a given practice, while some parcel spatial characteristics, objectives of forestland ownership, and landowners' concerns all have significant impacts on the choice probabilities.

The calculated carbon sequestration trends of four different management practices show that the choice of fertilization only or no management can sequester more carbon than practices which include fuel treatment. We also find that an incentive payment for fertilization that does not restrict the choice of fuel treatment may reduce the carbon sequestration potential as the payment level increases, because as the incentive payment goes up the choice of fertilization and fuel treatment crowds out the choice of no management, which has a larger carbon sequestration potential than fertilization and fuel treatment. These results highlight potential tradeoffs between management objectives, as activities designed to enhance resistance to fire, the quality of remaining trees, and biodiversity do not always increase carbon sequestration potential.

Our simulations of changes in carbon sequestration potential in response to incentive payments show that targeting the choice of fertilization only yields the highest carbon sequestration potential. Additionally, our results suggest that a carbon-based payment scheme can produce more carbon sequestration than a practice-based payment. However, a comparison of carbon sequestration supply with other studies shows that the annual carbon sequestration potential through changing management practices is not as large as that created through afforestation. This implies that the cost of carbon sequestration using intermediate forest management is relatively high compared to carbon sequestered using afforestation.

Finally, note that the incentive payment strategies considered here only focus on carbon sequestration as an environmental benefit. If the incentive policy targets other environmental benefits such as biodiversity, soil erosion, and water quality, the net effects of an incentives program will depend on the correlation among the environmental benefits considered.

Endnotes

[1] In 2007 private individuals, corporations, and other private groups owned 423 million acres (56%) out of 751 million acres of forest land in the US (Smith et al. 2009).

[2] Intermediate management practices are silvicultural treatments conducted to improve timber productivity and enhance resistance to potential hazards such as fire and disease while the stands are growing. Intermediate management involves practices that improve site quality such as fertilization, thinning, and fuel treatment, or improve resistance to pests and insects (IPCC 2000; North et al. 2009; McKinley et al. 2011).

[3] Pattanayak et al. (2002) provide empirical evidence confirming joint production of timber and nontimber amenities by private forest owners.

[4] Copies of the questionnaires used in the survey are available at http://www.fia.fs.fed.us/nwos/.

[5] The NWOS sample locations correspond to the plot center of the FIA inventory plots (Butler et al. 2005). A certain percentage of randomly chosen plots is fuzzed within a buffer area of 0.5 to 1 miles around each plot, and swapped with similar plots in the same county to protect landowner privacy, because FIA has a policy of nondisclosure of

exact locations due to confidentiality issues. However, the effect of perturbing and swapping on analyses using FIA data is negligible if the study area is large enough (McRoberts et al. 2005).

[6] More precisely, the no management option refers to a landowner who did not choose fertilization, fuel treatment, or a combination of the two. The landowner may have implemented other management activities not included in the NWOS survey, but this is not relevant for the purposes of this analysis, which focuses on the choice between the listed options.

[7] Because of the lack of identifiable information of each landowner's harvested and replanted trees, we assume all landowners plant and harvest their trees.

[8] $$SEV_{ik} = \frac{\sum_{t=0}^{T} (P_{ikt} Q_{ikt} - C_{ikt})(1+r)^{T-t}}{(1+r)^{t} - 1}$$

[9] The discount rate and time horizon were chosen for comparability with other studies following Stavins and Richards (2005).

[10] We assume 30 bags (80 lb/bag) per trip (Hanley et al. 2006).

[11] The Forest Vegetation Simulator (FVS) is an individual tree growth model widely used in the U.S. to support decision making on various forest management issues such as silvicultural prescriptions, fuel treatment, insect and disease impacts, and wildlife habitat management. The spatial scale of the FVS can vary from a single stand to thousands of stands. The stand growth simulation models can differ depending on the geographic region by applying regionally specific model variants (Crookston and Dixon 2005). The FVS is a very flexible carbon accounting tool, since it can consider the spatial heterogeneity of each forest parcel and can be applied with various silvicultural forest management activities.

[12] To simulate tree growth with different management options using FVS, we need to define a general silvicultural treatment rule for each management practice. In the case of fuel treatment, we followed the US Forest Service guide to fuel treatment in the western US (Johnson et al. 2007). We apply four silvicultural options (thinning from below to 50 trees per acre (tpa), 100 tpa, 200 tpa, and 300 tpa with 18 bdh limit with surface fuel removal) to calculate trends of stand volume and carbon sequestration potential. In the case of fertilization, we use application of 200 pounds of nitrogen per acre, since the FVS supports only this option.

[13] Stand density index (SDI) is a measure of stocking of tree stands based on the number of trees per acre (Avery and Hurkhart 2002).

[14] Average marginal effects are calculated using the following formula: $\partial \mathrm{Pr}_{ik} \big/ \partial z_{ik}^{j} = \mathrm{Pr}_{ik} \cdot \left[\beta_k^j - \sum_k \left(\mathrm{Pr}_{ik} \cdot \beta_k^j \right) \right]$, where z_{ik}^{j} and β_k^j are the *j*th elements of vectors z_{ik} and β_k, respectively.

[15] The semi-elasticities are calculated as the percentage point change in the probability of adopting a certain combination for a 1% change in the net returns for each choice.

[16] Actual probabilities of management choices weighted by acreage are 12.1% with fertilization and fuel treatment, 3.9% with fertilization only, 48.2% with fuel treatment only, and 35.8% with no management. We also use Theil's Inequality Coefficient to validate the model further by comparing actual choices and predicted choices (Langpap and Wu 2008). The coefficient is 0.11 which indicates a good predictive performance (the coefficient ranges between 0 and 1 with a value of 0 indicating a perfect prediction).

[17] The carbon accumulation trend for fertilization and fuel treatment is calculated by combining management rules from fuel treatment and fertilization.

[18] Since the data on landowners' management choices correspond to the years 2002 - 2006, our simulation is calibrated to begin in 2006. We use the *Carbon Report in the Fire and Fuel Extension of Forest Vegetation Simulator (FFE–FVS)* (Hoover and Rebain 2011), which accounts for carbon in above ground live trees, below ground live trees, below ground dead trees, standing dead trees, down dead wood, the forest floor, the understory, wood products in use, products in landfills, and carbon emitted from combustion.

[19] Baseline Carbon Sequestration (Mt/acre) = $\sum_{i=1}^{N}\left(\bar{C}_{ik} \times Acreage_i \Big/ \sum_{i=1}^{N} Acreage_i\right)$, where $\bar{C}_{ik}$ is the amount of carbon stored per acre for management option k with the highest predicted probability and $Acreage_i$ is acreage of forestlands owned by each individual landowner i.

[20] Note that this is comparable to removing incentives for the 'Fuel Treatment' choice.

[21] The contract length of federal conservation payment programs is 10-15 years for the Conservation Reserve Program (CRP), 5-10 years for the Wildlife Habitat Incentives Program (WHIP), and 6 years for the Environmental Quality Incentives Program (EQIP) (USDA Natural Resources Conservation Service 2008).

[22] It is difficult to choose the appropriate range of incentive payment since there are no comparable examples from previous studies of intermediate forest management choices. Therefore, we chose the range of incentive payments based on the average range of maximum carbon price from US EPA (2005) and the U.S. Agricultural Sector Model (Lewandrowski et al. 2004).

[23] The amount of carbon sequestration achieved in the long-run is uncertain since it is unknown when each plot will be harvested. If we knew the distribution of final harvest schedules of these forestlands, we could calculate the expected amount of carbon sequestered in the long-run. However, since the distribution of the harvest schedule is unknown, we only account the amount of carbon sequestered within the duration of a contract.

[24] Additionally, the adoption rate of the choice fertilization only starts decreasing at payments above $50/acre because the own marginal effect of the annual LTV of fertilization and fuel treatment is higher than that of fertilization only. Results showing the probability of choosing different management options as a function of annualized payments per acre are available upon request.

[25] We do not consider implementation costs for measurement, monitoring, and verification when comparing the cost of carbon between a practice-based scheme and a carbon-based scheme. If they were taken into account, the carbon sequestration potential under a carbon-based approach could be more costly than our estimate because generally measurement and monitoring costs are greater under a carbon-based scheme than under a practice-based scheme.

[26] The exception is no management at higher payment levels. This is because as the payment increases relatively more high cost-high benefit landowners choose this option under a carbon-based payment, while more low cost-low benefit landowners enroll under a practice-based payment. The difference in benefits is small, and the adoption rate increases faster with the payment under a practice-based payment scheme. Hence, for high enough payment levels the practice-based scheme outperforms the carbon-based scheme for no management.

[27] We only consider the carbon sequestration potential within the duration of the contract. These results might change if carbon flows after the termination of the contract are considered.

[28] Stavins and Richards (2005) conclude that after normalization to 1997 dollars, the cost of carbon for afforestation ranges from $28/Mt to $83/Mt for 272 MMt of national scale annual carbon sequestration, and from $33/Mt to $99/Mt for 454 MMt of national scale annual carbon sequestration.

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Table 1. Variable Description and Summary Statistics

Variable	Variable description	Mean	Std.Dev.
Annual Net Returns			
LTV Fert. & Fuel Treat.	Annual LTV of Fuel Treatment-Fertilization ($/acre)	41.127	53.172
LTV Fertilization	Annual LTV of Fertilization only ($/acre)	45.478	59.001
LTV Fuel treatment	Annual LTV of Fuel treatment only ($/acre)	43.297	56.565
LTV No Management	Annual LTV of No management ($/acre)	42.628	54.604
Owner's Demographic Characteristics			
Age	Age of landowner	62.814	11.461
Income less than $50K	1 if household income is less than $50,000, 0 otherwise	0.306	0.461
Income $50K - $100K	1 if household income is between $50,000 and $100,000, 0 otherwise	0.345	0.476
Income $100K - $200K	1 if household income is between $100,000 and $200,000, 0 otherwise	0.189	0.392
Income above $200K	1 if household income is more than $200,000, 0 otherwise	0.160	0.367
Education: Elementary and middle school	1 if landowner's education level is elementary or middle school, 0 otherwise	0.191	0.393
Education: High school	1 if landowner's education level is high school, 0 otherwise	0.329	0.470
Education: College	1 if landowner's education level is college, 0 otherwise	0.261	0.440
Education: Graduate	1 if landowner's education level is graduate or professional school, 0 otherwise	0.218	0.414
Occupation Farming	1 if landowner's occupation related to farming, logging, or timber industry, 0 otherwise	0.162	0.369
Owner's Attributes			
Primary Residence	1 if landowner is living within a mile of his/her forest, 0 otherwise	0.439	0.497
Manager	1 if landowner's decision making relies on experts such as land manager, forester, or logging contractor, 0 otherwise.	0.125	0.331
Biodiversity Objective	1if objective of owning forest is biodiversity, 0 otherwise	0.635	0.482
Timber Objective	1if objective of owning forest is timber harvest, 0 otherwise	0.265	0.442
Recreation Objective	1if objective of owning forest is recreation, 0 otherwise	0.483	0.500
Privacy Objective	1if objective of owning forest is privacy, 0 otherwise	0.655	0.476
Development Concern	1 if landowner concerned about development, 0 otherwise	0.425	0.495
Air Quality Concern	1 if landowner concerned about air quality, 0 otherwise	0.298	0.458
Disease Concern	1 if landowner concerned about insects and forest disease, 0 otherwise	0.577	0.495
Fire Concern	1 if landowner concerned about forest fire risk, 0 otherwise	0.622	0.485
Cost share	1 if landowner has participated in a forestry-related cost-share program, 0 otherwise	0.175	0.381
Certification	1 if landowner has knowledge about green certification, 0 otherwise	0.230	0.421
Non-timber products	1 if landowner harvested non-timber food products from his/her forest in recent 5 years, 0 otherwise	0.125	0.331
Acquisition Method: Bought	1 if acquisition method is "bought", 0 otherwise	0.620	0.486

Table 1 - Continued

Forestland Characteristics			
Forest Acres	Acres of forest owned inside of the state (1,000 acres)	1.366	2.617
Stand Density	Stand Density Index (100s trees per acre)	2.749	2.192
PNW	1 if forest located in the Pacific Northwest, 0 otherwise	0.216	0.412
PSW	1 if forest located in the Pacific Southwest, 0 otherwise	0.281	0.450
NRMT	1 if forest located in the N. Rocky Mountains, 0 otherwise	0.138	0.346
SRMT	1 if forest located in the S. Rocky Mountains, 0 otherwise	0.365	0.482
Low Slope	1 if average slope lower than 35 degree, 0 otherwise	0.651	0.477
Distance to Road	Distance from the site to main road (miles)	4.814	5.168
Number of Mills	Number of mills within 50 miles	8.733	12.182
Major species: Pine	1 if major species is pine, 0 otherwise	0.265	0.442
Major species: Other softwoods	1 if major species is other softwoods, 0 otherwise	0.349	0.477
Major species: Hard-hardwoods	1 if major species is hard-hardwoods, 0 otherwise	0.285	0.452
Major species: Soft-hardwoods	1 if major species is soft-hardwoods, 0 otherwise	0.101	0.302
Year: 2003	1 if survey year is 2003, 0 otherwise	0.314	0.465
Year: 2004	1 if survey year is 2004, 0 otherwise	0.218	0.414
Year: 2006	1 if survey year is 2006, 0 otherwise	0.468	0.499

Table 2. Marginal Effects of Probabilities of Choosing Alternative Management Practices

Variables	Choice 1: Fuel treatment & Fertilization	Choice 2: Fertilization only	Choice 3: Fuel treatment only	Choice 4: No management
Annual Net Returns				
LTV (Fert. & fuel treat.)	0.005 (0.001)***	-0.004 (0.002)*	-0.006 (0.003)**	0.005 (0.003)
LTV (Fertilization)	0.000 (0.001)	0.007 (0.002)***	-0.006 (0.004)	-0.001 (0.005)
LTV (Fuel treatment)	-0.004 (0.001)***	-0.001 (0.002)	0.022 (0.003)***	-0.017 (0.004)***
LTV (No management)	-0.002 (0.002)	-0.003 (0.003)	-0.010 (0.005)*	0.015 (0.007)**
Owners' Demographic Characteristics				
Age	0.001 (0.001)	0.000 (0.001)	-0.001 (0.002)	-0.001 (0.002)
Income (less than $50K)	-0.014 (0.025)	-0.078 (0.034)**	0.100 (0.046)**	-0.009 (0.046)
Income ($100K-$200K)	-0.013 (0.029)	-0.037 (0.035)	0.117 (0.051)**	-0.067 (0.050)
Income (more than $200K)	0.012 (0.031)	-0.055 (0.039)	0.125 (0.056)**	-0.081 (0.056)
Education (Elementary and middle school)	-0.020 (0.029)	-0.053 (0.040)	-0.020 (0.054)	0.093 (0.055)*
Education (College)	0.017 (0.025)	-0.042 (0.033)	-0.008 (0.048)	0.032 (0.048)
Education (Graduate)	-0.050 (0.033)	-0.045 (0.038)	-0.058 (0.052)	0.152 (0.051)***
Occupation Farming	0.019 (0.034)	-0.100 (0.045)**	0.099 (0.056)*	-0.017 (0.057)
Owners' Attributes				
Primary Residence	-0.008 (0.021)	0.100 (0.028)***	0.101 (0.038)***	-0.193 (0.037)***
Manager	-0.027 (0.029)	0.018 (0.043)	0.128 (0.056)**	-0.119 (0.061)*
Biodiversity Objective	-0.035 (0.022)	-0.053 (0.029)*	0.123 (0.040)***	-0.034 (0.040)
Timber Objective	-0.001 (0.027)	-0.039 (0.037)	0.134 (0.047)***	-0.094 (0.051)*
Recreation Objective	0.032 (0.021)	0.046 (0.028)*	-0.059 (0.038)	-0.019 (0.038)
Privacy Objective	-0.063 (0.022)***	-0.047 (0.031)	-0.113 (0.040)***	0.223 (0.042)***
Development Concern	0.063 (0.024)***	-0.064 (0.03)**	0.038 (0.041)	-0.037 (0.041)
Disease Concern	-0.005 (0.026)	0.099 (0.039)**	-0.047 (0.049)	-0.048 (0.049)
Air Quality Concern	-0.021 (0.023)	0.046 (0.033)	-0.023 (0.043)	-0.002 (0.045)
Fire Concern	-0.011 (0.027)	-0.109 (0.035)***	0.240 (0.053)***	-0.120 (0.053)**
Cost Share	0.093 (0.022)***	0.044 (0.034)	-0.215 (0.053)***	0.078 (0.054)
Certification	0.006 (0.023)	0.027 (0.032)	0.079 (0.046)*	-0.113 (0.047)**
Non-timber Products	0.005 (0.025)	0.069 (0.034)**	0.053 (0.054)	-0.127 (0.058)**
Acquisition method: Bought	0.035 (0.026)	0.052 (0.035)	-0.016 (0.045)	-0.071 (0.044)
Forestland Characteristics				
Forest Acres	0.002 (0.003)	0.002 (0.006)	0.001 (0.007)	-0.005 (0.008)
Stand Density	0.011 (0.006)*	-0.005 (0.009)	0.000 (0.013)	-0.005 (0.013)
PNW	0.015 (0.036)	-0.001 (0.052)	0.003 (0.072)	-0.016 (0.072)
PSW	-0.003 (0.030)	-0.094 (0.042)**	0.117 (0.057)**	-0.021 (0.056)
NRMT	0.016 (0.037)	0.008 (0.045)	0.123 (0.063)**	-0.148 (0.066)**
Low Slope	0.035 (0.023)	-0.028 (0.028)	0.101 (0.04)**	-0.108 (0.038)***

Table 2 - Continued

Distance to road	0.001 (0.002)	0.004 (0.002)*	-0.012 (0.004)***	0.006 (0.004)*
Number of Mills	0.001 (0.001)	-0.001 (0.002)	0.001 (0.002)	-0.001 (0.002)
Major species: Pine	0.031 (0.05)	-0.026 (0.044)	-0.057 (0.071)	0.052 (0.068)
Major species: Other softwoods	0.034 (0.049)	-0.085 (0.043)**	-0.050 (0.068)	0.101 (0.064)
Major species: Hard-hardwoods	0.058 (0.052)	0.055 (0.045)	-0.160 (0.079)**	0.047 (0.074)
Survey year 2004	0.036 (0.034)	-0.044 (0.036)	0.061 (0.050)	-0.052 (0.050)
Survey year 2006	0.072 (0.030)**	-0.089 (0.032)***	0.012 (0.048)	0.004 (0.047)
No. of Observations	513			
McFadden's R^2	0.374			
Log-likelihood	-371.184			
AIC	2.071			
BIC	-1460.5			
Correct prediction (1^{st} choice)	0.684			
Correct prediction (1^{st}& 2^{nd} choice)	0.924			

Note: *, **, *** Statistical significance at α = 10, 5, and 1 %. Parentheses are standard errors.

Table 3. Annual Carbon Sequestration Potential with Respect to Incentive Payments for the Western US

Payment Targets	Practice-based payment				Carbon-based payment			
	Payment ($/acre)							
	10	50	100	150	10	50	100	150
Fertilization	1.14	3.20	4.70	5.86	1.75	4.5	5.51	6.04
Fertilization & Fuel treatment	0.58	1.14	0.85	0.09	1.00	2.09	2.24	2.10
No management	1.05	2.29	3.29	3.44	1.62	2.41	2.93	3.44
Fertilization & No management	1.29	2.88	3.66	3.98	2.32	4.15	5.49	5.92

Table 4. Marginal Effects of Probabilities of Choosing Alternative Management Practices excluding observations with occupation related to farming, logging, or timber industry

Variables	Choice 1: Fuel treatment & Fertilization	Choice 2: Fertilization only	Choice 3: Fuel treatment only	Choice 4: No management
Annual Net Returns				
LTV (Fert. & fuel treat.)	0.006 (0.002)***	-0.006 (0.003)**	-0.007 (0.003)**	0.007 (0.004)*
LTV (Fertilization)	-0.001 (0.001)	0.010 (0.003)***	-0.006 (0.004)	-0.003 (0.005)
LTV (Fuel treatment)	-0.004 (0.001)***	-0.002 (0.002)	0.021 (0.003)***	-0.015 (0.004)***
LTV (No management)	-0.001 (0.002)	-0.003 (0.003)	-0.008 (0.005)*	0.012 (0.007)*
Owners' Demographic Characteristics				
Age	0.001 (0.001)	0.000 (0.001)	0.000 (0.002)	-0.001 (0.002)
Income (less than $50K)	0.003 (0.029)	-0.089 (0.039)**	0.075 (0.052)	0.011 (0.053)
Income ($100K-$200K)	-0.001 (0.032)	-0.048 (0.037)	0.101 (0.053)*	-0.051 (0.052)
Income (more than $200K)	0.016 (0.034)	-0.058 (0.04)	0.086 (0.058)	-0.044 (0.058)
Education (Elementary and middle school)	-0.091 (0.04)**	-0.016 (0.045)	0.001 (0.061)	0.106 (0.062)*
Education (College)	0.009 (0.028)	-0.028 (0.037)	-0.041 (0.051)	0.059 (0.051)
Education (Graduate)	-0.060 (0.035)*	-0.028 (0.04)	-0.051 (0.054)	0.138 (0.053)***
Owners' Attributes				
Primary Residence	-0.008 (0.023)	0.115 (0.03)***	0.084 (0.04)**	-0.192 (0.039)***
Manager	-0.034 (0.032)	0.021 (0.047)	0.120 (0.06)**	-0.107 (0.065)
Biodiversity Objective	-0.053 (0.026)**	-0.058 (0.032)*	0.157 (0.043)***	-0.046 (0.044)
Timber Objective	0.011 (0.031)	-0.049 (0.042)	0.148 (0.052)***	-0.110 (0.057)*
Recreation Objective	0.009 (0.024)	0.034 (0.03)	-0.026 (0.04)	-0.018 (0.04)
Privacy Objective	-0.048 (0.024)*	-0.045 (0.035)	-0.098 (0.045)**	0.190 (0.047)***
Development Concern	0.081 (0.027)***	-0.079 (0.032)**	0.025 (0.042)	-0.027 (0.042)
Disease Concern	-0.002 (0.028)	0.113 (0.042)***	-0.062 (0.051)	-0.049 (0.051)
Air Quality Concern	-0.007 (0.024)	0.052 (0.034)	-0.057 (0.044)	0.012 (0.046)
Fire Concern	-0.006 (0.03)	-0.117 (0.037)***	0.231 (0.056)***	-0.108 (0.055)**
Cost Share	0.103 (0.026)***	0.054 (0.038)	-0.132 (0.059)**	-0.025 (0.061)
Certification	-0.021 (0.027)	0.041 (0.036)	0.062 (0.052)	-0.081 (0.054)
Non-timber Products	0.000 (0.028)	0.066 (0.037)*	0.074 (0.056)	-0.140 (0.06)**
Acquisition method: Bought	0.041 (0.03)	0.066 (0.037)*	-0.027 (0.048)	-0.079 (0.046)*
Forestland Characteristics				
Forest Acres	0.004 (0.004)	0.005 (0.006)	0.003 (0.008)	-0.012 (0.009)
Stand Density	0.016 (0.007)**	-0.005 (0.009)	-0.005 (0.013)	-0.006 (0.013)
PNW	0.030 (0.041)	0.008 (0.056)	-0.068 (0.079)	0.031 (0.078)
PSW	0.011 (0.036)	-0.116 (0.046)**	0.136 (0.061)**	-0.032 (0.06)
NRMT	0.048 (0.041)	-0.067 (0.055)	0.136 (0.068)**	-0.118 (0.074)
Low Slope	0.043 (0.03)	-0.033 (0.03)	0.113 (0.043)***	-0.124 (0.04)***
Distance to road	0.001 (0.002)	0.004 (0.003)	-0.011 (0.004)***	0.006 (0.004)

Table 4 – Continued

Number of Mills	0.002 (0.001)*	-0.002 (0.002)	0.003 (0.003)	-0.002 (0.003)
Major species: Pine	0.015 (0.052)	-0.017 (0.048)	0.002 (0.076)	0.000 (0.071)
Major species: Other softwoods	-0.001 (0.051)	-0.056 (0.046)	0.008 (0.073)	0.049 (0.068)
Major species: Hard-hardwoods	0.036 (0.058)	0.078 (0.048)	-0.171 (0.084)**	0.056 (0.077)
Survey year 2004	-0.016 (0.047)	-0.032 (0.041)	0.164 (0.061)***	-0.116 (0.057)**
Survey year 2006	0.054 (0.03)*	-0.084 (0.034)**	0.050 (0.05)	-0.019 (0.048)
No. of observations	430			
McFadden's R^2	0.422			
Log-likelihood	-290.370			
AIC	2.076			
BIC	-1080.7			
Correct prediction (1st choice)	0.737			
Correct prediction (1st& 2nd choice)	0.916			

Note: *, **, *** Statistical significance at α = 10, 5, and 1 %. Parentheses are standard errors.

Table 5. Annual Carbon Sequestration Potential at $80/Mt with Alternative Discount Rates in the Western US

Payment Targets	Practice-based payment			Carbon-based payment		
	Carbon, million metric ton					
	3%	5%	7%	3%	5%	7%
Fertilization	0.60	1.51	1.51	3.12	3.83	4.04
Fertilization & Fuel treatment	0.12	0.46	0.46	0.46	1.06	1.33
No management	1.17	1.04	0.92	2.01	2.01	1.91
Fertilization & No management	1.39	2.17	2.71	2.97	3.96	5.04

Table 6. Annual Carbon Sequestration Potential at $80/Mt with Alternative Contract Durations in the Western US

Payment Targets	Practice-based payment			Carbon-based payment		
	Carbon, million metric ton					
	5-year	10-year	15-year	5-year	10-year	15-year
Fertilization	1.01	1.51	1.30	2.55	3.83	3.83
Fertilization & Fuel treatment	0.37	0.46	0.45	0.68	1.06	0.81
No management	0.97	1.04	0.91	2.11	2.01	1.97
Fertilization & No management	1.81	2.17	2.12	2.96	3.96	3.70
Average	0.99	1.21	1.13	2.08	2.72	2.58

Figures

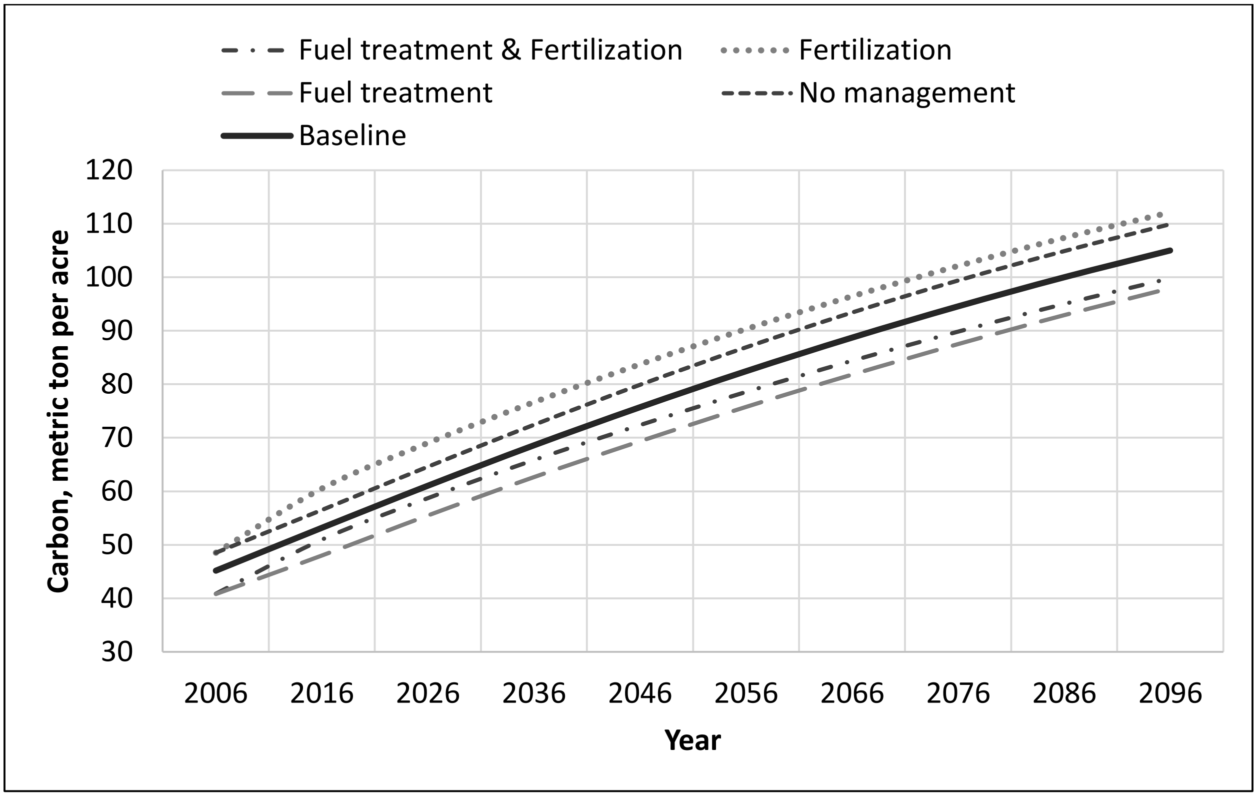
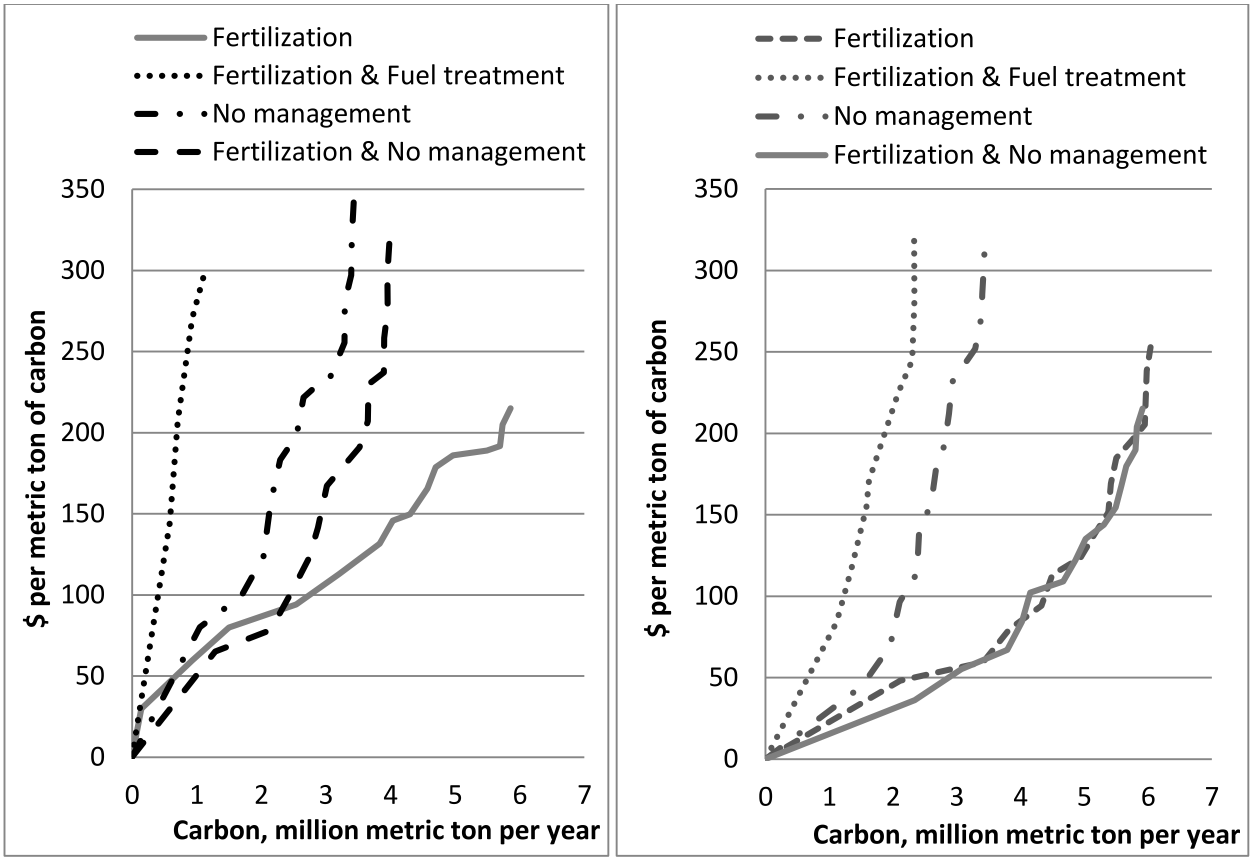


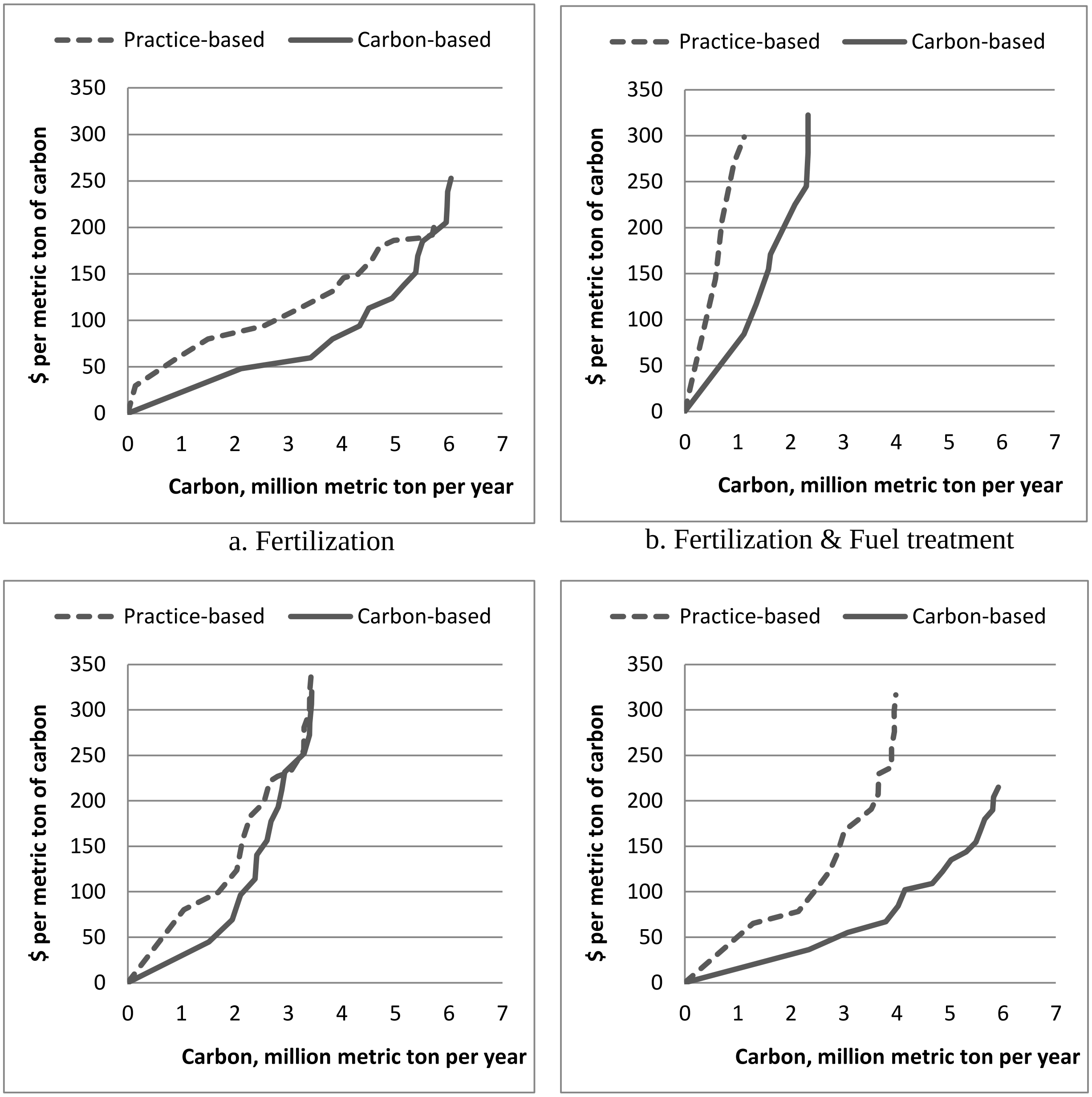
Figure 1. Carbon Accumulation with Different Management Practices



a. Practice-based payment

b. Carbon-based payment

Figure 2. Carbon Supply Functions for Each Management Option for the Western US



a. Fertilization

b. Fertilization & Fuel treatment

c. No management

d. Fertilization & No management

Figure 3. Carbon Supply Functions under Different Payment Schemes for the Western US

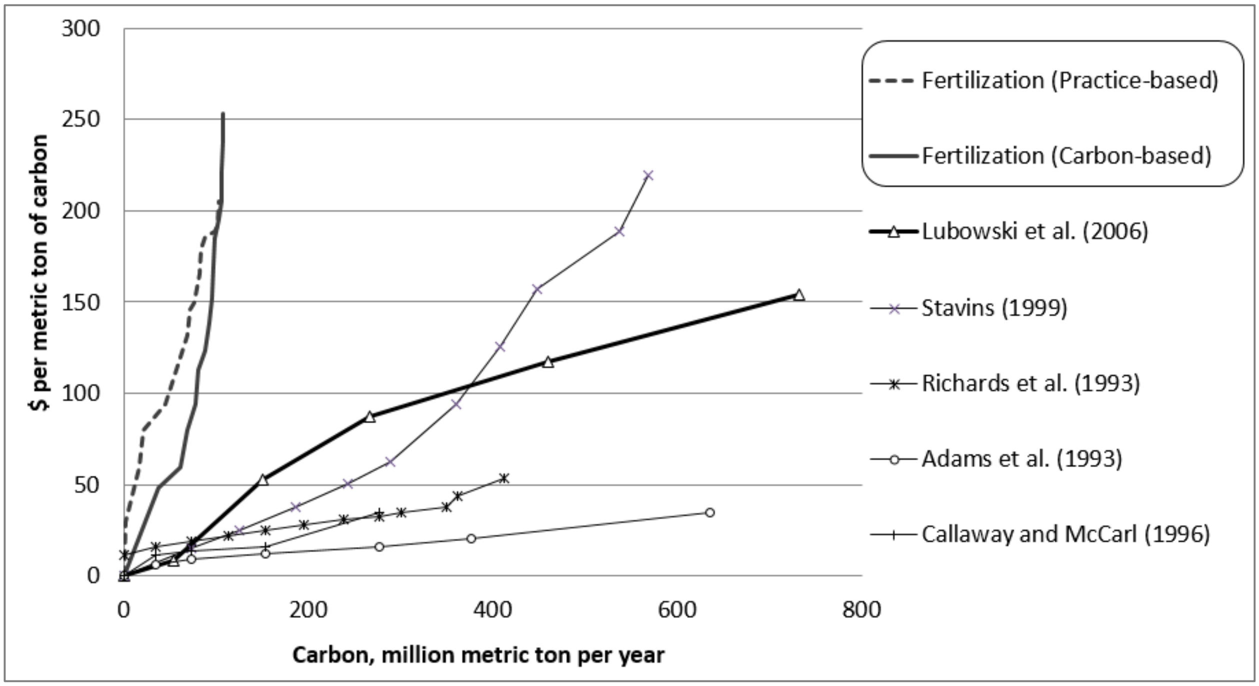


Figure 4. Comparison of Normalized Carbon Supply Functions for Intermediate Management Practices and Afforestation

Note: All carbon supply functions except the two from this study are from Lubowski et al. (2006).

Appendix

Table A1. Estimated Coefficients for Multinomial Logit Model

Variables	Choice 1: Fuel treatment & Fertilization	Choice 2: Fertilization only	Choice 3: Fuel treatment only
Annual Net Returns			
LTV (Fert. & fuel treat.)	0.104 (0.044)**	-0.059 (0.033)*	-0.035 (0.025)
LTV (Fertilization)	0.004 (0.044)	0.080 (0.043)*	-0.025 (0.037)
LTV (Fuel treatment)	0.000 (0.041)	0.050 (0.035)	0.158 (0.030)***
LTV (No management)	-0.113 (0.069)*	-0.083 (0.051)	-0.101 (0.050)**
Owners' Demographic Characteristics			
Age	0.020 (0.025)	0.008 (0.017)	0.000 (0.012)
Income (less than $50K)	-0.208 (0.700)	-0.886 (0.487)*	0.486e (0.346)
Income ($100K-$200K)	0.055 (0.796)	-0.205 (0.501)	0.767 (0.379)**
Income (more than $200K)	0.758 (0.856)	-0.364 (0.563)	0.891 (0.418)**
Education (Elementary and middle school)	-0.895 (0.794)	-0.950 (0.578)*	-0.449 (0.402)
Education (College)	0.315 (0.699)	-0.597 (0.479)	-0.120 (0.353)
Education (Graduate)	-1.946 (0.900)**	-1.067 (0.544)**	-0.878 (0.384)**
Occupation Farming	0.661 (0.933)	-1.107 (0.641)*	0.557 (0.409)
Owners' Attributes			
Primary Residence	0.652 (0.596)	1.837 (0.421)***	1.131 (0.297)***
Manager	-0.076 (0.829)	0.610 (0.637)	0.980 (0.441)**
Biodiversity Objective	-0.631 (0.623)	-0.519 (0.422)	0.646 (0.303)**
Timber Objective	0.502 (0.750)	-0.133 (0.542)	0.959 (0.367)***
Recreation Objective	0.813 (0.579)	0.622 (0.400)	-0.164 (0.283)
Privacy Objective	-2.602 (0.642)***	-1.350 (0.468)***	-1.405 (0.329)***
Development Concern	1.817 (0.647)***	-0.595 (0.443)	0.407 (0.303)
Disease Concern	0.002 (0.709)	1.328 (0.562)**	-0.066 (0.364)
Air Quality Concern	-0.567 (0.631)	0.542 (0.475)	-0.133 (0.329)
Fire Concern	0.450 (0.755)	-0.876 (0.526)*	1.537 (0.419)***
Cost Share	1.829 (0.654)***	0.284 (0.512)	-1.144 (0.429)***
Certification	0.679 (0.651)	0.714 (0.468)	0.777 (0.352)**
Non-timber Products	0.672 (0.723)	1.248 (0.525)**	0.700 (0.431)
Acquisition method: Bought	1.159 (0.723)	0.864 (0.492)*	0.225 (0.328)
Forestland Characteristics			
Forest Acres	0.060 (0.092)	0.045 (0.083)	0.025 (0.055)
Stand Density	0.298 (0.176)*	-0.042 (0.127)	0.036 (0.095)
PNW	0.448 (1.001)	0.048 (0.737)	0.092 (0.532)
PSW	0.141 (0.841)	-1.030 (0.603)*	0.624 (0.419)
NRMT	1.128 (1.029)	0.611 (0.666)	1.120 (0.485)**
Low Slope	1.432 (0.639)**	0.054 (0.403)	0.905 (0.295)***
Distance to road	-0.016 (0.053)	0.030 (0.033)	-0.077 (0.03)**
Number of Mills	0.032 (0.030)	-0.007 (0.026)	0.008 (0.018)

Table A1 - Continued

Major species: Pine	0.537 (1.341)	-0.476 (0.63)	-0.401 (0.507)
Major species: Other softwoods	0.435 (1.315)	-1.335 (0.623)**	-0.533 (0.483)
Major species: Hard-hardwoods	1.120 (1.422)	0.503 (0.650)	-0.835 (0.572)
Survey year 2004	1.194 (0.918)	-0.329 (0.521)	0.525 (0.361)
Survey year 2006	1.851 (0.821)**	-1.030 (0.463)**	0.156 (0.351)
Constant	-9.195 (2.556)***	-2.282 (1.518)	-1.935 (1.115)*
No. of observations	513		
McFadden's R^2	0.374		
Log-likelihood	-371.184		
AIC	2.071		
BIC	-1460.448		
Correct prediction (1st choice)	0.684		
Correct prediction (1st& 2nd choice)	0.924		

Note: *, **, *** Statistical significance at α = 10, 5, and 1 %. Parentheses are standard errors.