Private Landowners' Response to Incentives for Carbon Sequestration in Forest Management

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Selected paper prepared for presentation at the Agricultural & Applied Economics Association's 2012 AAEA Annual Meeting, Seattle, Washington, August 12-14, 2012

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1. Introduction

There is widespread recognition of the potential role forests can play in contributing to Green House Gas reductions through carbon sequestration (Brand 1998; Metz et al. 2001, Lubowski et al. 2006). Nonindustrial private forests (NIPFs) comprise a significant portion of forests in the U.S.[1] Thus, it is crucial to assess the role that NIPF landowners can play in broader carbon sequestration efforts. NIPF ownership characteristics and management information, as well as their spatial characteristics, are essential for understanding NIPF owners' forest management choices.

Management actions by NIPF owners that could increase carbon sequestration on their lands include afforestation of land used for agriculture, reforestation, changing forest management such as increasing rotation length, fire control, fertilization, thinning and pruning, or choosing alternative tree species (Stainback and Alavalapati 2002, Sohngen and Mendelsohn 2003, Shaikh et al. 2007). It is generally known that paying incentive for carbon sequestration in forest is relatively low cost option (e.g. Alig, R. J. 2003, Lubowski et al. 2006, Mason et al. 2010). However, existing studies on landowners' response to carbon sequestration incentives have largely focused on afforestation and reforestation (Adams et al. 1993, Alig et al. 1997, Parks and Hardie 1995, Plantinga et al. 1999, Stavins 1999, Newell and Stavins 2000, Lubowski et al. 2006).

[1] Of the 490 million acres of timberland in the US, Federal, State, and local governments own 131 million acres (27%) and non-industrial private entities own 288 million acres (59%) <http://www.epa.gov/oecaagct/forestry.html>.

Changing management practices (MPs) in existing forests has been often mentioned as a source of carbon sequestration as well. Many studies have shown the potential for forest carbon sequestration by adopting a certain forest management practices. For example, Row (1996) concluded that change in forest management can increase carbon sequestration by 0.6-0.8 metric tons (Mt) of carbon per acre per year in the cases of loblolly pines in Southeast and Douglas Fir in the Pacific Northwest.[2] IPCC (2000) shows that forest management activities such as regeneration, fertilization, choice of species and reduced forest degradation have the potential to sequester around 0.2 Mt per acre per year in developed countries. Intermediate forest MPs which is conducted to increase tree growth rate or enhance resistance from hazard can be a source of carbon sequestration as well.[3] Watson et al. (2001) estimated that fertilization can increase carbon storage in Canadian forests by 0.03-0.19 Mt per ha per year. Grayston (2006) concluded based on his reviews that nitrogen fertilization can increase aboveground biomass of boreal and temperate forests, and also increases soil carbon, while fertilization can be a source of N_2O and CH_4 emissions.[4] In the case of activities controlling fire hazard, North et al. (2009) concluded that thinning and prescribed burning allow greater long-term storage of carbon since they yield bigger and more fire-resistant trees and decrease the intensity of future wildfires, although they decrease total carbon storage in the short run. On the other hand, Ryan et al. (2010) argued that while thinning is an effective forest management technique used to reduce fire risk, increase tree resistance to insect and disease, and increases the growth of the remaining individual trees, it

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[2] Carbon in wood products is also included.

[3] Intermediate management practice is a regimen of silvicultural treatments designed to tend to stands between their formation and their final harvest. Intermediate management can involve practices that improve the site (e.g. fertilization, fuel treatment) or manage pests and insects, as well as partial harvesting (e.g. thinning) <http://www.forestencyclopedia.net/p/p1696>.

[4] Grayston (2006) mentioned that fertilization can be a source of N_2O and CH_4 emissions, however in contrast to agriculture fertilization have limited effects on them. Pang and Cho (1984) also showed nitrogen fertilization can be a negligible source of N_2O emissions from forest soils.

decreases overall forest wood growth until the remaining trees grow enough to reoccupy the site, so that the carbon stock in a thinned stand is generally lower than that in an unthinned stand.[5] Law and Harmon (2011) also argued that forest management needs to reduce above-ground biomass by as much as 40–50% to achieve a significant level of fire severity reduction. This would result in a net emission of CO_2 to the atmosphere from forests as the amount of carbon removed is greater than that saved by changing fire behavior. Although these studies have shown the potential of carbon sequestration by changing forest MPs, the MP changes introduced in these studies are not correspond to landowners' responses with respect to various factors such as annual net returns, and individual characteristics affecting their MP decisions. Thus, it is hard to know what factors affect landowners' MP choices and how much the cost of carbon sequestration is by adopting a certain MP.

There are several studies which examine landowners' forest MP decisions and carbon sequestration potentials in economic perspectives. For example, Plantinga and Birdsey (1993) developed a carbon budget model to examine the effects of forest MPs on carbon storage in private forests, and showed that changes in forest carbon inventory result from tree growth and management activities, in particular harvesting. Englin and Callaway (1993) showed that the optimal rotation age of Douglas-fir with payment for carbon sequestration is longer than the traditional Faustmann rotation age and is positively correlated with the price of carbon. Van Kooten et al. (1995) examined the implications of carbon subsidies and taxes for economically optimal harvest decisions and found that rotation ages would increase by roughly 20 percent over the level where no carbon costs or benefits are considered. Sohngen and Brown (2008) showed that around 55 MMt of carbon (15 million tCO_2) can be sequestered at less than \$25.7/Mt

[5] This is because even 100% use of the harvested trees for products or biomass energy may not produce a total carbon benefit greater than that of the higher storage and storage rate in an unthinned stand.

(\$7/tCO_2) and around 766 MMt of carbon (209 million tCO_2) can be sequestered at \$202/Mt (\$55/tCO_2) of carbon price by extending rotation ages in softwood forests in 12 states of the southern and western US. Zyrina (2000) estimated the cost of carbon sequestration with different MP regimes, and showed the carbon storage increases from 428 Mt/ha to 589 Mt/ha with a marginal cost of \$13.28/Mt, and from 683 Mt/ha to 802.7 Mt/ha with a marginal cost of \$32.79/Mt. These studies suggest that incentive programs including taxes or carbon payments or other types of subsidies can impact the management decisions of forest in ways that can lead to increased carbon sequestration. However, most of them have focused on rotation length and harvest decision, and few have focused on other silvicultural management activities such as fertilization and thinning. In addition, one important drawback of these studies is that most of them have analyzed the carbon sequestration effects of the forest management activities independently, while in practice these activities may be conducted jointly rather than independently within certain range of forestland.

One important advantage of this study is the use of survey data which describe the NIPF landowners' management practice choices, and their demographic characteristics, resource characteristics, and other attributes which can affect landowners' decision of management practices.[6] The survey-based approach can capture various factors affecting forest management decisions which are rarely taken into account in conventional econometric approaches using historical data.

The main purpose of this study is to examine private landowner response to incentives for carbon sequestration through combinations of intermediate MPs of existing forests, and to

[6] There are survey-based studies have shown how landowner attributes and incentives shape forest management decisions for other environment services such as biodiversity and endangered species (e.g. Nagubadi et al. 1996; Conway et al. 2003; Langpap 2004, 2006), but not for carbon sequestration especially through intermediate forest managements.

measure the carbon sequestration potential of these forest management combinations given different levels of incentive payments.

The study results show that the factors affecting the probabilities of adopting intermediate MPs of forests differ by the choice of MPs. The own marginal effects and elasticities of the probabilities of choosing the MPs with respect to expected net returns are all positive and significantly different from zero, which is consistent with expectations of economic theory. Landowners' demographic characteristics do not significantly affect the probability of choosing a certain MP, while the spatial characteristics, objectives of owning forestlands, and concerns they have faced tend to affect these probabilities significantly. The calculated carbon sequestration trends of four different MPs show that the choice of 'Fertilization' or 'No Activity' can sequester more carbon than the choice including 'Fuel Treatment', which suggests that the fact that activities enhancing resistance from fire, quality of remaining trees, and biodiversity, do not always increase the carbon sequestration potentials. The simulation of carbon sequestration potentials in response to incentive payments with different targeting strategies shows that targeting the choice of 'fertilization' yields the highest carbon sequestration potential, and a performance-based payment scheme produces higher carbon sequestration than a practice-based payments scheme. However, the comparison of the supply function of carbon sequestration with afforestation studies shows that the annual carbon sequestration potential through changing intermediate MPs of NIPFs in the western US is not as large as that through afforestation.

The remainder of this paper is organized as follows. Section 2 presents the conceptual background and model specification, the data description, and the analysis of the econometric model. Section 3 presents baseline carbon sequestration potentials, the incentive payment design, and the simulation of carbon sequestration potentials with different incentive payments strategies. Section 4 includes a discussion of the main findings and the conclusion.

2. Econometric Analysis

2.1. Conceptual Background and Model Specification

In this section, I describe the conceptual background of NIPF landowner's forest management decision models and the econometric model. A utility maximization framework is the starting point to evaluate NIPF landowners' forest management activity choices (Pattanayak et al. 2000). Consider a utility-maximizing NIPF landowner who is faced with various combinations of forest management practices. Since forest management activities can be conducted jointly within the same area of forestland, suppose the NIPF landowner can choose among K different combinations of forest MPs, with $k = 0$ indicating no forest MPs and $k = 1,2,\ldots,K$ indicating the set of mutually exclusive combinations of forest MPs. The NIPF owner maximizes expected utility from managing forestlands by adopting a combination of MPs: combination k $(k=1,2,\ldots,K)$ will be chosen if $U_k > U_j$ for all $k \neq j$, where U_k is the utility of adopting combination k.

Since the landowner' utility can be affected by both observable and unobservable components, the landowner's MPs decision problem can be modeled using a general random utility (RUM) approach (Lubowski et al. 2002; Cooper 2003). Let $U_{ik}(Z_{ik})$ be the expected utility of NIPF landowner i from choosing a combination of MPs k on her forestland. The utility depends on vector of variables $Z_{ik} = [X_{ik}, W_i]$, where X_{ik} is a vector of attributes of forest management choices such as expected net returns, which varies across the forest management choices and across the individual landowners. W_i is a vector of individual landowners' characteristics and their land characteristics which varies only over the landowners (Greene 2006; Lubowski 2002). By considering both observable and unobservable components of NIPF landowners' management decision, $U_{ik}(Z_{ik})$ can be considered a random variable and be written as:

$$U_{ik}(Z_{ik}) = Z_{ik}^{'}\beta_k + \varepsilon_{ik},\ k = 0,1,2,...,K\ . \tag{1}$$

where β_k are parameters for each variable and ε_{ik} is a random error term. The probability that NIPF owner *i* will choose the forest MPs combination *k* is:

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

If we assume the error term ε_{ik} is independently and identically distributed with the extreme value distribution, then the probability that NIPF owner *i* will adopt intermediate forest MP choice *k* can be specified using a multinomial logit model *(*McFadden 1974; Maddala 1983*).* The MNL model for the choice of intermediate forest MPs can be written as

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

Then, the log-likelihood function is:

$$\log L = \sum_{i}^{N}\sum_{k}^{K} d_{ik}\log\left(P_{ik}\right) \tag{4}$$

where d_{ik} = 1 if individual *i* chooses alternative *j* and d_{ik} = 0 otherwise.

2.2. Data description

We use data from National Woodland Owner Survey (NWOS), which describes private woodland owners' forest management behaviors, landowners' attributes, and land characteristics surveyed by the US Forest Service from 2002 to 2006, to analyze the factors affecting landowners' forest management decision (http://www.fia.fs.fed.us/nwos/).[7] There are a total of 593 observations which cover the Western United States (AZ, CO, CA, ID, MT, NM, OR, UT, WA, and WY). Of these, 513 observations are defined as NIPFs owners. The spatial location of plots of individual forestlands is also provided, which allows us to incorporate the stand information of each forestland from the Forest Inventory and Analysis (FIA) constructed by the USDA Forest Service.

The forest management activities included in the NWOS data are: i) Partial harvest to improve the growth of remaining trees (Thinning), ii) Fire hazard reduction, and iii) Fertilization. Since most landowners who adopt thinning for remaining trees also conduct fire hazard reduction to improve fire tolerance, and thinning is commonly considered as a type of activity to control fire hazard, we combined thinning and fire hazard control together as one type of intermediate forest MP, fuel treatment. Thus, the choices of intermediate forest MPs are: Fertilization–Fuel Treatment (FFT), Fertilization only (F), Fuel Treatment only (FT), and No activities (NA).

We calculate the owner-specific expected net returns with different choice of intermediate forest MPs as one of key explanatory variables to examine the NIPF owners' responses. As a measure of annual net returns, we use the annualized value of Land and Timber Stands (LTV) (Latta and Montgomery 2004). Because of the lack of identifiable information of

[7] The National Woodland Owner Survey (NWOS) is the official census of forest owners in the United States. It is aimed at increasing understanding of woodland owners who are the critical link between forests and society (*http://www.fia.fs.fed.us/nwos/*).

each landowner's harvested and replanted trees, we assume all NIPFs landowners plant and harvest their trees. The LTV for each MP choice *k* and landowner *i*, based on the current stand volume is:

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

where T is the final harvest year, t^0 is the current year, P_{ikt} is stumpage price for i and k at year t, Q_{ikt} is the per acre harvest volume for i and k at year t, C_{ikt} is the per acre cost of stand treatments applied for i and k at year t, ω is a maximum range of 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 then annualized the LTV using a 5% discount rate over a 100-year period. Owner-specific forest management costs (C_{ikt}) for fuel treatment are calculated by using the fuel reduction cost simulator (FRCS) which is used to estimate the cost of fuel reduction activities by considering stand volumes and each forestland's spatial characteristics such as distance from site to closest main road, average slope, and elevation (Fight et al. 2006). The range of fertilization cost is used the results from previous studies (e.g. Shumway and Atkinson 1978, Miller and Fight 1979, Dickens et al. 2003). We then normalized the cost based on application time and amount, and differentiated based on average slope and distance from main road. The site specific stand volume (Q_{ikt}) with various management combinations is calculated using the Forest

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

Vegetation Simulator (FVS).[9] Location information (Longitude and Latitude) of each forestland plot allow us to incorporate forest inventory data (e.g. tree species, stand age, slope, elevation, etc) which is necessary to run FVS.

To simulate tree growth with different choices of MPs using FVS, we need to define a general silvicultural treatment rule of each MP. In the case of fuel treatment, we followed the guide to fuel treatment in the western US published by Johnson et al. (2007) of the USDA Forest Service, so that 4 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) are applied to calculate trends of stand volume and carbon sequestration potentials. In case of fertilization, application of 200 pounds of nitrogen per acre is used, since FVS supports only this option.

We categorized the owner-specific variables used in the econometric model as follows: Landowner's demographic characteristics, resource and spatial characteristics, and landowner's attributes. At first, landowner's demographic characteristics which are taken from NWOS include age, level of education, level of household income, and occupation. Several studies have shown that age has a positive correlation with adoption of soil conservation practices (Ervin and Ervin 1982), while it has a negative correlation on harvesting and investment on silvicultural activities (Beach et al. 2005). However, some studies argued that age does not significantly affect timber harvest behavior and the forestry cost share program (Dennis 1989, Nagubadi et al. 1996). It is also argued that income is negatively correlated with timber harvest (Dennis 1989,

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

1990; Beach et al. 2005), and positively correlated with silvicultural management activities (Beach et al. 2005). But several studies found that both income and education do not significantly affect forest owners' management decision (Dennis 1989, Langpap 2006). The landowners whose occupation is farm or forest related are positively and significantly correlated with timber harvest (Beach et al. 2005).

Regarding the resource characteristics, it is known that site quality and stand volume increase the amount of silvicultural activities (Zhang and Pearse, 1996) and harvests (Dennis 1990), while size of forestland has a positive effect on silvicultural activities in around 40% of the studies cited in Beach et al. (2005). It is also generally recognized that greater stand volume, larger plot size, flatter average slope (below 35-40 degree), higher incidence of mills close to the site, and shorter distance from the site to a main road, all reduce forest management costs, which may induce more intermediate MPs or harvesting (Cubbage 2004, Latta and Montgomery 2004, Fight et al. 2006, Zhou and Kockelmen 2008). Based on this information, resource characteristics taken from NWOS include size of forestlands owned within a state, forest regions (Pacific Northwest, Pacific Southwest, and Northern Rocky Mountain). Additionally, we create individual land's spatial characteristic variables by overlapping the location information (Longitude and Latitude) of each forestland with other spatial data from Forest Inventory Analysis (FIA) and the US Geological Survey (USGS), which include stand density index (SDI), slope dummy (below 35 degree or not), distance from site to main road, and number of mills within 50 miles from the site.

Finally, landowners' attributes taken from NWOS include: objectives of owning forestland, concerns faced recently (concerns about future development, air quality, insects and disease, and risk of fire), whether a landowner is living within a mile of forestland or not, whether a landowner is a main decision maker of management or not, program enrollment or knowledge (cost-share program, and knowledge about green certification), whether a landowner recently harvested non-timber products or not, and land acquisition method. Landowners who own forests for commercial purposes are more likely to invest in silvicultural MPs such as thinning to improve quality of timber; hence they may be less likely to participate in the program to prevent such activities. On the other hand, we expect that landowners who own forests for privacy or recreational opportunities may be less likely to invest in timber harvest or silvicultural MPs. Some studies mentioned that development pressure can affect land use choice (Mansfield et al. 2000, Kristensen et al. 2001), but it is unclear how landowners who are concerned about future development act for their forests. We expect that landowners who are under pressure of development might invest more to increase their property value, but are less willing to participate in the program to provide environmental services. Many studies mentioned that landowners who are under pressure of fire risk, insect, and disease tend to harvest earlier and invest more for intermediate MPs such as fuel treatment and risk control practice by thinning (Reed 1984; Amacher et al. 2005; Neheker et al. 2005; Konoshima et al. 2008). We also expect that if landowners who live within a mile of their forests, and if the main decision makers are in forest-related professions such as logging contractor and forester, they are more likely to conduct forest management practices. Program enrollment such as cost sharing and technical assistance has positive effects on encouraging silvicultural treatment (Beach et al. 2005). In this study, the participation dummy of cost sharing program and knowledge about green certification are available to use from NWOS for econometric analysis. Table 1 presents the descriptions and summary statistics of all of these variables.

Table 1. Variable description and summary statistics

Variable	Variable description	Mean	Std.Dev.
Annual Net Returns			
AnnLTV1	Annual LTV of Fuel Treatment-Fertilization ($/acre)	41.374	53.538
AnnLTV2	Annual LTV of Fertilization only ($/acre)	45.699	59.207
AnnLTV3	Annual LTV of Fuel treatment only ($/acre)	43.297	56.565
AnnLTV4	Annual LTV of No activity ($/acre)	42.628	54.604
Demographic Characteristics			
AGE	Age of landowners	62.814	11.461
INCOME1-4	Dummies: Household income, less than $50,000 (1) to $200,000 or more (4). Income4 is used as a reference group in the econometric model.	-	-
EDU1-5	Dummies: Education level of landowner, less than high school (1) to graduate or professional school (5). EDU1 used as reference group.	-	-
OCCU_farm	Dummy: Occupation related to farming, logging, and timber industry	0.162	0.369
Resource Characteristics and Spatial Characteristics			
FOREST_ACRE	Acres of forestland owned inside of the state (1,000 ac)	1.366	2.617
SDI	Stand Density Index	274.871	219.218
PNW	Dummy: Pacific Northwest	0.216	0.412
PSW	Dummy: Pacific Southwest	0.281	0.450
NRMT	Dummy: Northern Rocky Mountain	0.138	0.346
SLOPE_low	Dummy: Average slope lower than 35 degree	0.634	0.482
DISTANCE_S2R	Dummy: Distance from the site to main road	4.814	5.168
NUM_MILLS50	Number of mills within 50 miles	8.733	12.182
Landowner attributes			
PRIMARY_Resident	Dummy: Owners living within a mile of forestland	0.439	0.497
MANAGER	Dummy: Main decision maker is experts related with forests (e.g. logging contractor, forester) rather than family	0.125	0.331
OBJ_bio	Dummy: Objective of owning for biodiversity	0.635	0.482
OBJ_timber	Dummy: Objective of owning for timber harvest	0.265	0.442
OBJ_recreation	Dummy: Objective of owning for recreation	0.483	0.500
OBJ_privacy	Dummy: Objective of owning for privacy	0.655	0.476
CONCERN_develop	Dummy: Concern about development	0.425	0.495
CONCERN_air	Dummy: Concern about air quality	0.298	0.458
CONCERN_disease	Dummy: Concern about insects and diseases	0.577	0.495
CONCERN_fire	Dummy: Concern about risk of fire	0.622	0.485
COSTSHARE	Dummy: Participated in a cost-share program	0.175	0.381
KNOW_GREEN	Dummy: Knowledge about green certification	0.230	0.421
NON-TIMBERPROD	Dummy: Recently harvested non-timber food products	0.125	0.331
ACQ_bought	Dummy: Land acquisition method: bought	0.620	0.486

2.3. Model Estimates and Interpretation

We specify the component of individual landowner *i*'s utility of MP choice *k* as follows:

$$U_{ik} = \alpha_k + \beta_k AnnLTV_{ik} + \gamma_k^1 OWN_{ik} + \gamma_k^2 LC_{ik} + \gamma_k^3 OA_{ik} + \varepsilon_{ik},\ k = FFT, F, FT, NA. \quad (1)$$

where $AnnLTV_{ik}$ is a vector of annual LTVs, OWN_{ik} is a vector of landowners' demographic characteristics, LC_{ik} is a vector of forestland characteristics, OA_{ik} is a vector of landowners' attributes, and ε_{ik} is a random error term, for landowner *i* and MP choice *k*.

The estimated parameters allow us to analyze the determinants of NIPFs owners' choices of management practice combinations. Since the interpretation of coefficients in a multinomial logit model is difficult, the marginal effects[10] are used to examine what determinants affect NIPFs owners' choices of MPs. Table 2 shows the marginal effects of the explanatory variables, calculated using the model coefficients and the sample means of the variables. The main variables of interest are annual LTVs (*AnnLTV1~4*) of forest MPs as proxies of expected net returns. The own marginal effects with respect to LTVs are all positive and significant at least at the 10% significance level, which implies that an increase in the LTV for a forest MP will increase the likelihood that the forest MP will be chosen. 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 the choice 'FFT (Fertilization-Fuel Treatment)' decreases the probability of choosing choice 'F (Fertilization) and 'FT (Fuel Treatment)'. The higher annual LTV for the choice 'FT' decreases the probability of choosing other MPs significantly.

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

In cases of marginal effects with respect to landowners' demographic characteristics, age (*AGE*) and household income dummy (*INCOME*) do not significantly affect the probability of choosing MPs. Education dummies (*EDU*) do not significantly affect the choice of MPs as well, except that landowners with $50,000 to $100,000 of household income are less likely to choose 'FT'. The landowners whose occupation is related to farm or forests (*OCCU_farm*) are more likely to adopt 'FT', which is consistent with other studies showing that it is positively and significantly correlated with timber harvest (Beach et al. 2005). While each of the landowners' demographic characteristics does not significantly affect the probability of choosing a certain MP, the test for the joint significance of each equation rejects the null hypothesis that all coefficients associated with landowners' demographic characteristics are zero at the 10% significant level.

In cases of marginal effects on the probability of choosing 'FFT (Fertilization and Fuel Treatement)' with respect to resource characteristics and landowners' attributes, results suggest that the probability of choosing 'FFT' increase with higher in-stand density index (*SDI*), which is consistent with previous studies mentioned in Beach et al. (2005).[11] It has positive effects on the probability of choosing 'FFT' with landowners who own their forests for recreation (*OBJ_recreation*), who have concerns about future development (*CONCERN_develop*), and who have enrolled in a cost share program (*COSTSHARE*), while it has negative effects for those landowners who have concerns about privacy. (*CONCERN_privacy*).

The marginal effects on probability of choosing 'F (Fertilization)' with respect to resource characteristics and landowners' attributes indicate that landowners who live within a mile of their forests (*PRIMARY_resident*), distance from site to main road (*DISTANCE_S2R*),

[11] Stand density index (SDI) is a measure of stocking of tree stands based on the number of trees per unit area and diameter at breast height (DBH) of stand trees of average basal area (Avery and Hurkhart 2002).

landowners who have concerns about insects and diseases (*CONCERNS_insects*), and who produce non-timber food products (*NTFP_recent*) have positive effects on the possibility of choosing 'F', while landowners who owns their forests for biodiversity (*OBJ_bio*), who have concerns about future development (*CONCERN_develop*), and who have concerns about fire hazard (*CONCERN_fire*) are less likely to choose 'F'.

The marginal effects on probability of choosing between 'FT (Fuel Treatment)' and 'NA (No Activity)' have opposite signs in most cases. Those landowners with forest lands located in the northern rocky mountain (*NRMT*) region are more likely to adopt 'FT', but less likely to choose 'NA'. The marginal effect of distance from the site to a main road (*DISTANCE_S2R*) shows that the further away from a main road a site is, the less likely a landowner is to 'FT', and more likely to choose 'NA'. The landowners who live within a mile of their forestlands (*PRIMARY_resident*), who are consulted by non-family experts (*MANAGER*; e.g. logging contractor, forester, and business partner), who own lands for biodiversity (*OBJ_bio*) and timber harvest (*OBJ_timber*), and are concerned about risk of fire (*CONCERN_fire*) are more likely to choose 'FT', but less likely to choose 'NA'.[12] On the other hand, those landowners who own forests for recreation (*OBJ_recreation*) and privacy (*OBJ_privacy*) are less likely to choose 'FT', but more likely to choose 'NA'. In addition, the landowners who have knowledge about green certification, and who produce non-timber food products are less likely to choose 'NA'. These results are consistent with our expectations and the results of previous studies (Mansfield et al. 2000, Kristensen et al. 2001, Amacher et al. 2005; Neheker et al. 2005; Konoshima et al. 2008,

[12] It is generally known that thinning for fuel treatment can enhance the fire resistance of remaining trees (North et al 2009; Ryan et al. 2010). And Muir et al. (2002) mentioned that thinning on young forests may increase vegetative structure for a variety of plant and wildlife species, and also concluded the total abundance of birds is greater in thinned young- and old-growth stands than in un-thinned stands.

Table 2. Marginal Effects of probabilities of choosing alternative MPs

Variables	Choice 1: Fuel treatment & Fertilization	Choice 2: Fertilization only	Choice 3: Fuel treatment only	Choice 4: No activity
AnnLTV1	0.0043 (0.0014)***	-0.0039 (0.0021)*	-0.0057 (0.0029)**	0.0054 (0.0035)
AnnLTV2	-0.0001 (0.0011)	0.0068 (0.0025)***	-0.0065 (0.0042)	-0.0003 (0.0055)
AnnLTV3	-0.0030 (0.0013)**	-0.0007 (0.0021)	0.0204 (0.0034)***	-0.0167 (0.0037)***
AnnLTV4	-0.0013 (0.0017)	-0.0030 (0.0027)	-0.0079 (0.0052)	0.0122 (0.0071)*
Age	0.0006 (0.0009)	0.0008 (0.0012)	-0.0011 (0.0016)	-0.0003 (0.0016)
D_income50	-0.0209 (0.0322)	-0.0122 (0.046)	-0.0245 (0.0582)	0.0577 (0.0613)
D_income50-100	-0.0156 (0.0301)	0.0521 (0.0397)	-0.1092 (0.0551)**	0.0727 (0.0558)
D_income100-200	-0.0238 (0.0329)	0.0157 (0.0439)	-0.0059 (0.0588)	0.0141 (0.0609)
D_education3	0.0155 (0.0289)	0.0478 (0.0411)	0.0249 (0.0541)	-0.0882 (0.055)
D_education4	0.0267 (0.0298)	0.0257 (0.0444)	0.0126 (0.0582)	-0.0650 (0.0595)
D_education5	-0.0228 (0.0348)	0.0065 (0.0477)	-0.0437 (0.0621)	0.0599 (0.0626)
Occupation_farmer	-0.0141 (0.0283)	-0.0658 (0.0439)	0.0994 (0.0505)**	-0.0195 (0.0533)
Manager_nonfamily	-0.0100 (0.0276)	0.0101 (0.0444)	0.1206 (0.0564)**	-0.1207 (0.0614)**
Forest_acreage	0.0022 (0.003)	0.0027 (0.0053)	0.0030 (0.0069)	-0.0079 (0.0078)
SDI	0.0001 (0.0001)*	0.0000 (0.0001)	0.0000 (0.0001)	0.0000 (0.0001)
d_pnw	0.0182 (0.0347)	-0.0091 (0.0527)	-0.0071 (0.0717)	-0.0021 (0.0717)
d_psw	0.0159 (0.0269)	-0.0276 (0.0369)	0.0447 (0.0482)	-0.0329 (0.0486)
d_nw	0.0153 (0.0368)	-0.0051 (0.0467)	0.1222 (0.0619)**	-0.1324 (0.0661)**
Slope_low35	0.0344 (0.0236)	-0.0218 (0.0283)	0.0994 (0.0399)**	-0.1120 (0.0385)***
Distance_site2road	0.0006 (0.0019)	0.0039 (0.0023)*	-0.0108 (0.004)***	0.0063 (0.0038)*
Num_mills_in50m	0.0010 (0.001)	-0.0005 (0.0018)	0.0006 (0.0023)	-0.0011 (0.0024)
Primary_resident	0.0018 (0.0204)	0.0907 (0.0286)***	0.0998 (0.0377)***	-0.1923 (0.0375)***
Objective_biodiversity	-0.0286 (0.0211)	-0.0509 (0.0296)*	0.1149 (0.04)***	-0.0354 (0.0405)
Objective_timber	0.0029 (0.0252)	-0.0520 (0.0369)	0.1382 (0.0471)***	-0.0892 (0.051)*
Objective_recreation	0.0392 (0.0207)*	0.0420 (0.0284)	-0.0645 (0.0374)*	-0.0168 (0.0381)
Objective_privacy	-0.0601 (0.0226)***	-0.0419 (0.0303)	-0.1210 (0.0406)***	0.2229 (0.0422)***
Concern_development	0.0567 (0.0222)**	-0.0719 (0.0308)**	0.0445 (0.0405)	-0.0292 (0.0416)
Concern_insects	0.0097 (0.0256)	0.0947 (0.0391)**	-0.0579 (0.049)	-0.0465 (0.049)
Concern_air	-0.0299 (0.0228)	0.0459 (0.0329)	-0.0174 (0.0433)	0.0014 (0.0455)
Concern_fire	-0.0050 (0.026)	-0.1100 (0.035)***	0.2374 (0.0527)***	-0.1224 (0.0526)**
Cost_share	0.0892 (0.0214)***	0.0369 (0.0341)	-0.2073 (0.0528)***	0.0812 (0.0542)
Green_certification	0.0074 (0.0231)	0.0206 (0.0326)	0.0718 (0.0456)	-0.0998 (0.0471)**
NTFP_recent	0.0074 (0.024)	0.0666 (0.0348)*	0.0558 (0.054)	-0.1298 (0.0585)**
Acquisition_bought	0.0341 (0.0273)	0.0385 (0.0334)	-0.0048 (0.0455)	-0.0678 (0.0438)

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

Beach et al. 2005) mentioned in the previous section. One interesting result is that enrollment into a cost share program affects ‘FFT’ and ‘FT’ in opposite directions, even if both conduct fuel treatment. However, since the purposes and types of cost sharing program that each landowner is enrolled in are unknown, it is difficult to explain why this is.

We also calculate the own- and cross-return semi-elasticities of the probability of choosing the different MP combinations with respect to annual LTVs (Table 3). 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. As shown in Table 3, for example, the own semi-elasticities of annual LTVs show that a 1% increase in LTV of each MP choice increases the probability of adopting the MP choices ‘FFT’, ‘F’, ‘FT’, and ‘NA’ by 0.20 percentage point (%p), 0.28 %p, 0.7 %p, and 0.41 %p, respectively. The cross-return semi-elasticities show that a 1% increase in annual LTV of choice ‘FFT’ reduces the possibility of choosing ‘F’ by 0.14 %p, and ‘FT’ by 0.22 %p. However, a 1% increase in annual LTV of choice ‘F’ or ‘NA’ does not significantly affect the probability of adopting other MPs, while a 1% increase in annual LTV of choice ‘FT’ reduces the probability of adopting the choice ‘FFT’ by 0.15 %p, and ‘NA’ by 0.52 %p.

Table 3. Semi-elasiticities of probabilities of choosing alternative MPs

Variables	FFT (Fertilization & Fuel treatment)	F (Fertilization only)	FT (Fuel treatment only)	NA (No activity)
AnnLTV1	0.204 (0.063)***	-0.139 (0.071)*	-0.218 (0.09)**	0.154 (0.109)
AnnLTV2	-0.002 (0.049)	0.282 (0.101)***	-0.249 (0.14)	-0.032 (0.19)
AnnLTV3	-0.147 (0.051)*	-0.035 (0.069)	0.699 (0.096)***	-0.517 (0.105)***
AnnLTV4	-0.056 (0.071)	-0.111 (0.096)	-0.238 (0.163)	0.405 (0.229)*

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

I use the predicted probabilities to predict the choice of a landowner's forest MP, so the choice of MP with the highest predicted probability is the predicted choice. This will allow us to calculate the baseline carbon sequestration potentials. Based on the predicted choices, 5.8% of landowners choose 'FFT', 3.7% choose 'F', 38.4% choose 'FT', and 52.0% choose 'NA'. Since each landowner owns forestland of different size, I also calculate predicted probabilities of MP choices weighted by acreage: 14.1% of forest acres are managed with 'FFT', 3.1% with 'F', 49.6% with 'FT', and 33.1% with 'NA'.[13] The model correctly predicts landowners' MPs choice at 70% and 91% of actual choices are predicted as the first or second choice by the models. I also used Theil's Inequality Coefficient to validate the model further by comparing actual choices and predicted choices (Leuthold 1975; Langpap and Wu 2008; Ahn et al. 2000). The coefficient is 0.12 which indicates a good predictive performance.[14]

3. Simulation of carbon sequestration with incentive payments

3.1. Calculation of carbon sequestration trend and baseline

To examine the potential of carbon sequestration through intermediate forest MPs, we only considered NIPF lands that are stocked with more than 50 trees per acre (tpa). Harvested or un-stocked lands are excluded. Since the landowners' choices of MPs come from the survey conducted from 2002 to 2006, we start to simulate the carbon sequestration trends with respect to

[13] Actual probabilities of MP choices weighted by acreage was 12.1% with 'FFT', 3.9% with 'F', 48.2% with 'FT', and 35.8% with 'NA'.
[14] Theil's Inequality Coefficients is a measure of forecasting accuracy. Leuthold (1975) mentioned that *"a value of 0 indicates perfect prediction, while a value of 1 corresponds to perfect in-equality or negative proportionality between the actual and predicted values.*" The coefficients in Langpap and Wu (2008) range between 0.007 and 0.17 in projection of different land use categories.

the choice of MPs from 2006 using the *Carbon Report in the Fire and Fuel Extension of Forest Vegetation Simulator (FFE–FVS)* (Hoover and Rebain, 2011).[15]

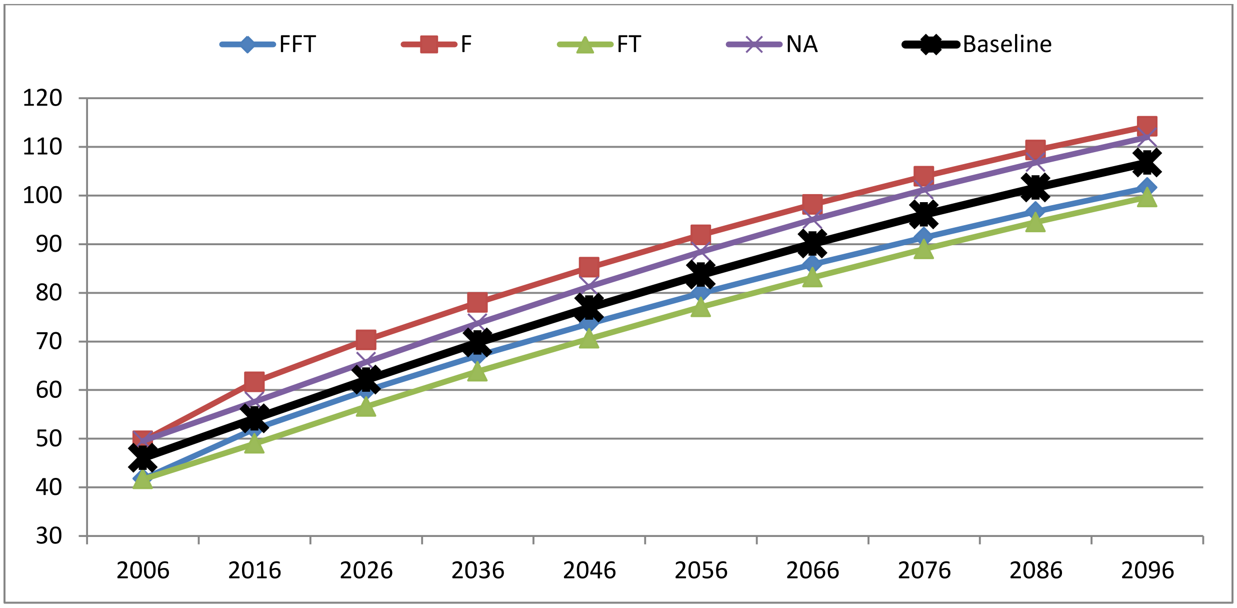
Figure 1 shows the carbon accumulation trends of different MPs and the baseline carbon sequestration potential based on the results of the econometric analysis and FVS, assuming that the trees keep growing with no harvest for 100 years. Carbon accumulation trends of each MP choice are calculated by assuming 100% of landowners choose one specific MP. Carbon accumulation of the MP choice 'FFT' is calculated by combining MP rules from 'FT' and 'F'. In Figure 1, the carbon accumulation trends of MPs show that the choice 'F' has the highest carbon sequestration potential, followed by 'NA'. Note that the carbon sequestration potential of 'NA' is always greater than that of 'FFT' and 'FT', which 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. This result is consistent with Ryan et al. (2010) and Law and Harmon (2011).[16]

Given the carbon sequestration of each MP choice, we calculate the baseline carbon sequestration trend per acre, which is the average of annual carbon accumulation of MPs weighted by the predicted probabilities of MP choices (i.e. 14.1% of forest acres are managed

[15] Carbon Report in FFE-FVS comprised with the Stand Carbon Report and Harvested Carbon Report. The Stand Carbon Report includes aboveground live tree, belowground live tree, belowground dead tree, standing dead trees, down dead wood, forest floor, and understory (shrubs/herbs). The Harvested Carbon Report includes products in use, products in landfills, and carbon emitted from combustion.
[16] We expect that the cost of carbon sequestration with consideration of fire risk can be higher than that we estimated, because the difference in carbon sequestration between thinned (the choice 'FFT' and 'FT') and unthinned (the choice 'F' and 'NA') stands can be decreased, carbon sequestration potential by converting MP can be reduced. Law and Harmon (2011) mentioned even if the risk of fire is considered, carbon sequestration potential with fuel treatment is lower than the no activity option. It implies that the amount of carbon loss caused by fuel treatment is larger than carbon sequestration caused by reducing the possibility of being fire.

with ‘FFT’, 3.1% with ‘F’, 49.6% with ‘FT’, and 33.1% with ‘NA’).[17] We assume that the predicted proportion of MPs will not change over time, if other conditions facing landowners remain the same over time.

Figure 1. Carbon accumulation with different MPs and baseline carbon accumulation (per acre)



3.2. Incentive payments design

The goal of the incentive payments program is to increase carbon sequestration by encouraging the NIPF owners to switch their current intermediate MP to alternative MPs. The simulation of carbon sequestration examines how the adoption rate of each MPs will change with incentive payments and measures how much carbon can be additionally sequestered with this

[17] 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 the MP k with the highest predicted probability, and $Acreage_i$ is acreage of forestlands owned by each individual landowner i.

change in adoption rate. I assume incentives are paid to NIPF owners to encourage implementation of forest MPs which can increase carbon sequestration. The effects of incentive payments to encourage a certain forest MP for carbon sequestration are simulated by changing the level of annual LTV of that particular MP choice given different level of payments. An incentive payment to adopt forest MP choice *k* increases the annual LTV of that MP, and therefore modifies the estimated adoption probabilities P_k as follows (Lubowski et al. 2006):

$$P_{ik} = f(\hat{\beta}_k, AnnLTV_{ik} + AnnPAY_{ik}, AnnLTV_{ij}, OWN_i, LC_i, OA_i)$$

where $\hat{\beta}_k$ is the vector of estimated parameters, $AnnLTV_{ik}$ is annual LTV of forest MP choice *k*, $AnnLTV_j$ is a vector of annual LTV of other MP choices, and $AnnPAY_{ik}$ is annual payments per acre for carbon sequestration which is annualized the incentive payment within duration of contract with 5% discount rate over 100 years.

We assume that no harvesting is allowed during the length of the contract. This is necessary because there is a time lag to achieve a certain level of carbon sequestration. We use the duration of a 10-year contract, and the sensitivity analysis will be followed with alternative duration of contracts.[18] Thus, we only consider the amount of carbon sequestered within the duration of a contract as additional carbon sequestration under the incentive payment,[19] and then we annualize the amount of carbon sequestration over 100-year time horizon.

[18] The contract length of federal conservation payment programs is 10-15 years for Conservation Reserve Program (CRP), 5-10 years for Wildlife Habitat Incentives Program (WHIP), and 6 years for Environmental Quality Incentives Program (EQIP) (See http://www.nrcs.usda.gov).

[19] 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.

Another relevant aspect of an incentive contract is the payment criterion. We consider two criteria, based on whether the goal of incentive payments is to change the intermediate MPs itself (practice-based contracts) or to change the environmental benefits, i.e. carbon sequestration through the change of MPs (performance-based contracts). Existing environmental policies such as Conservation Reserve Program (CRP), Environmental Quality Incentive Program (EQIP), and Wetland Reserve Program (WRP) have offered the payment 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 ecosystem (Antle et al. 2001). Antle et al (2003) found that performance-based contracts achieved greater benefits in soil carbon sequestration than practice-based contracts. In the following section, we simulate and compare the additional carbon sequestration based on both payment criteria.

Given the carbon sequestration trends for each MP choice shown in Figure 1, without considering the risk of fire, an increase in the adoption of ‘Fuel Treatment’ does not increase, and may even reduce the annual carbon sequestration rate, while an increase in the adoption of ‘Fertilization’ or ‘No activity’ 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 the MP choices of ‘Fertilization’ and ‘No activity’, which can also be considered a disincentive of the ‘Fuel Treatment’ choice. Hence, the possible combinations of the incentive payment targets can be classified as follows: i) Pay incentives for fertilization only, so only landowners who adopt the choice ‘F (Fertilization)’ will be paid and those who implement other activities are not eligible (i.e. payment for ‘F’), ii) Pay for the fertilization no matter what other combined activities are, so landowners who choose ‘FFT (Fertilization and Fuel Treatment)’ or ‘F (Fertilization)’ will be paid (i.e. payment for ‘FFT-T’), iii) Pay only for the choice ‘NA (No activity)’ so only landowners who make this choice will be paid (i.e. payment for ‘NA’), and iv) Pay for both ‘F (Fertilization)’ and ‘NA (No Activity)’, so the landowners who adopt fuel treatment are not eligible (i.e. payment for ‘F-NA’).

Finally, the impact of the incentive on carbon sequestration is calculated based on the net increment in the adoption rate of the specific MP choice relative to the baseline. Incentive payments used in simulation ranges in $10 increments from $0 to $150 per acre for the duration of contract.[20] A supply function of carbon sequestration can then be derived based on the annualized carbon price ($/Mt) and the corresponding annualized amount of carbon sequestration. Since this study focuses on the NIPF landowners in the western US, we define 42 million acres (62%) out of 68 million acres of total private lands as NIPF lands.[21]

3.3. Carbon Sequestration Potential under Practice-Based Payments

Suppose NIPF landowners are offered incentive payments to change their current MPs to practices that might lead to increased carbon sequestration, so that each landowner will receive incentive payments based on the acreage of lands enrolled in the program.

Suppose landowners are paid only for the choice ‘F (Fertilization)’, then the proportion of the choice ‘F’ increases as the payment level increases. Figure A1-a in appendix shows the probability of choosing MPs with respect to the annualized payments per acre for the choice ‘F’. As the payment level gets higher, the amount of carbon sequestration increases at a diminishing

[20] It is difficult to decide the range of incentive payment since there is no comparable examples from previous studies which elicit the decision of intermediate forest MP with response to incentive payments. Therefore, we decide the range of incentive payments where the adoption rate of MP converge a certain level.
[21] We define the NIPF lands as family and individual-owned forests based on NWOS, which include forest land owned by individuals, couples, estates, trusts, or other groups of unincorporated individuals. These represent 62 % of the private forest land, 92% of the private forest owners, and 35 percent of all forest land in the US (Smith et al. 2007).

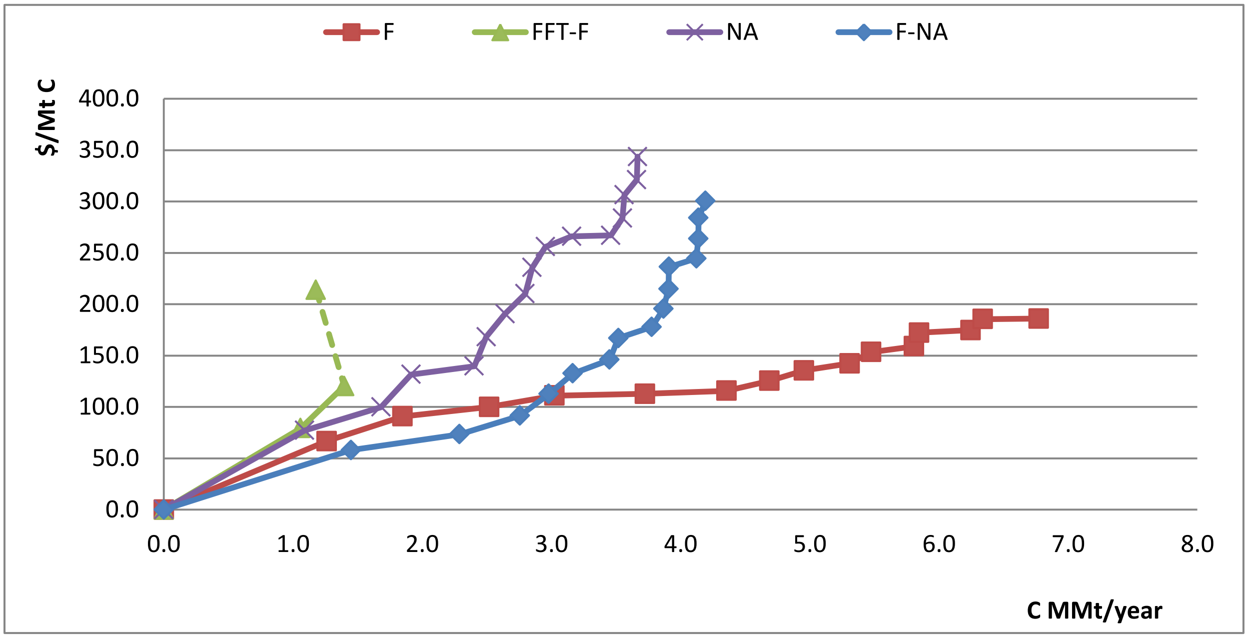
rate, because of a declining increment of adoption rate. Table 4 shows the corresponding carbon sequestration potential in the region within the duration of contract under the practice-based payment. The amount of incentive payment in this table implies the annual payment per acre paid for only within duration of contract. Suppose we pay from $10/acre to $150/acre of incentives for 10 years to landowners who adopt choice ‘F’, then the annual carbon sequestration potential ranges from 1.3 MMt to 6.8 MMt.

Table 4. Annual carbon sequestration potential under practice-based payment for each payment target

$/acre	F	FFT-F	NA	F-NA
10	1.26	1.06	1.09	1.45
50	3.72	1.53	2.50	3.17
100	5.48	0.84	3.16	3.91
150	6.77	0.09	3.67	4.19

Figure 2 shows the carbon supply function (marginal cost curve) in the western US with respect to the annualized carbon prices ($/Mt). The payment targeting for ‘F-NA’ produces the highest carbon sequestration potential at less than $105/Mt, while that for only ‘F’ produces the highest annual carbon sequestration with 0.9 MMt, 2.5 MMt, and 5.4 MMt, at the carbon price of $50/Mt, $100/Mt, and $150/Mt, respectively. The maximum available amount of annual carbon sequestration is 6.8 million metric tons (MMt) at a price of $186/Mt.

Figure 2. Carbon supply function under practice-based payment for each payment target



Now suppose the landowners are paid an incentive for adoption of fertilization no matter what other intermediate MPs are used. In this case, landowners who adopt the choice ‘FFT’ or ‘F’ are eligible to get paid (i.e. payment for ‘FFT-F’). As the payment level increases, the adoption rate of ‘FFT’ and ‘F’ increases at lower than the $50/acre annualized payment, but that of the choice ‘F’ begins to stop increasing and start decreasing at higher than $50/acre. This is because the own marginal effect of annual LTV of ‘FFT’ is higher than that of ‘F’ (Figure A1-b in appendix). In Table 4, if we pay from $10/acre to $150/acre of incentives for the duration of the contract to landowners who adopt the choice ‘FFT’ or ‘F’, the annual carbon sequestration potential ranges from 0.1 MMt to 1.5 MMt with a 10-year contract. In Figure 2, at the carbon price of $50/Mt, $100/Mt, and $150/Mt, the annual carbon sequestration potentials are 0.2 MMt, 1.2 MMt, and 1.3 MMt, respectively. As the level of annual payments increases, the carbon supply function begins to turn to a negative slope after achieving the maximum carbon sequestration. This is because the higher the proportion of those choosing ‘FFT’ induces the greatest loss in the proportion of those choosing ‘NA’ which has a larger carbon sequestration potential than ‘FFT’. Also note that the higher the proportion of choosing ‘FFT’ the lower the baseline carbon sequestration potential. The intuition behind this result is that a payment for fertilization with no restriction of choosing fuel treatment may reduce the carbon sequestration potential as the payment level increases.

Next, suppose landowners are paid to not carry out any management activities on their property (i.e. payment for ‘NA’). As the payment level increases, the adoption rate of ‘NA’ goes up at a decreasing rate as well, as shown in Figure A1-c. In Table 4, if landowners who adopt choice ‘NA’ are paid from $10/acre to $150/acre of incentives with a 10-year contract, the annual carbon sequestration ranges from 1.1 MMt to 3.7 MMt. This leads to additional carbon sequestration. As shown in Figure 2, the annual carbon sequestration potential for the strategy ‘NA’ is 0.7 MMt, 1.7 MMt, and 2.4 MMt, at price of $50/Mt, $100/Mt, and $150/Mt, respectively.

Finally, when landowners are paid an incentive to either not implement any management activities on their land or to fertilize (i.e. Payment for ‘F-NA’), then the adoption rates of both choices increase at a decreasing rate (Figure A1-d). By doing so, the amount of carbon sequestered increases at a decreasing rate as well. In table 4, if the level incentive payments range from $10/acre to $150/acre for only the duration of contract to landowners who adopt choice ‘F’ or ‘NA’, annual carbon sequestration ranges from 1.5 MMt to 4.2 MMt with a 10-year contract. In Figure 2, as the carbon prices change from $50/Mt, to $100/Mt and $150/Mt, annual carbon sequestration potential increases from 1.2 MMt to 2.8 MMt and 3.5 MMt.

3.4. Carbon Sequestration Potential under Performance-Based Payments

Now suppose the NIPF landowners are offered incentive payments based on the amount of carbon stored on their forestlands by adopting a certain MP over the duration of the contract, so that each individual is offered different amount of payments.

At first, when landowners are paid only for 'Fertilization (F)', the proportion of the choice 'F' increases at a diminishing rate as the payment level gets higher, as shown in Figure 2A-a in appendix. Table 5 shows the carbon sequestration potential in the western US with respect to the average annual payments paid for only within duration of the contract under the performance-based payment schemes. If we pay between \$10/acre and \$150/acre for only the duration of contract to landowners who adopt choice 'F', the annual carbon sequestration potential ranges from 2 MMt to 6.3 MMt.

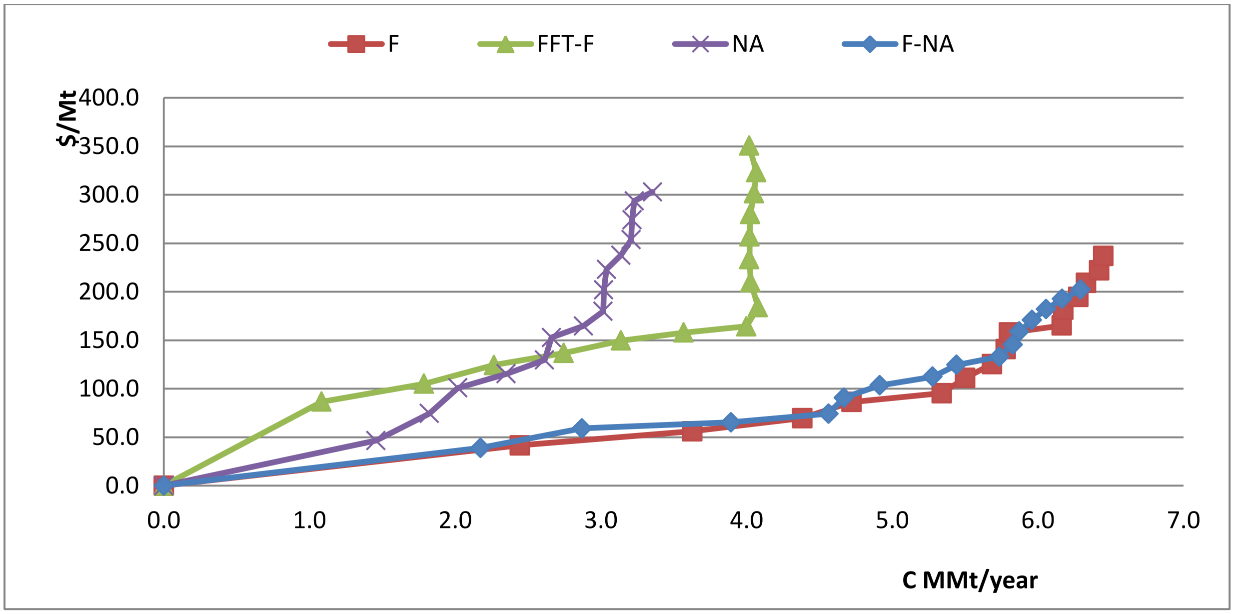
Table 5. Annual carbon sequestration potential under performance-based payment for each payment target

\$/acre	F	FFT-F	NA	F-NA
10	2.02	0.97	1.54	2.15
50	4.80	2.93	2.70	4.66
100	5.79	4.03	3.21	5.82
150	6.30	4.06	3.75	6.28

Note: the annual payment per acre within duration of contract is average of annual payments offered to individual landowners for the choice of MPs under performance-based scheme.

As shown in Figure 3, with a 10-year contract, the total annual carbon sequestration potentials in the western US are 3.1 MMt, 5.4 MMt, and 5.8 MMt at the price of \$50/Mt, \$100/Mt, and \$150/Mt, respectively.

Figure 3. Carbon supply function under performance-based payment for each payment target



Next, when the payment targets the choice ‘FFT’ or ‘F’ (i.e. payment for ‘FFT-F’), the adoption rates of both ‘FFT’ and ‘F’ increase as the payment level increases. In Table 5, the annual carbon sequestration potential corresponding to the annual payment (from $10/acre to $150/acre) ranges from 1 MMt to 4.1 MMt. Figure 3 shows, at $50/Mt, $100/Mt, and $150/Mt of carbon price, the annual carbon sequestration in the western US increases by 0.7 MMt, 2 MMt, and 4 MMt, respectively. However, after achieving the maximum level of carbon sequestration, the annual carbon sequestration rate stops increasing and begins to decline slightly as the payment increases. This is because the portion of the choice ‘NA’ that switches to the choice ‘FFT’ leads to a loss of carbon sequestration, and also because the carbon gain from an increment of the choice ‘F’ is almost similar or less than the carbon loss from an increment of the choice ‘FFT’.

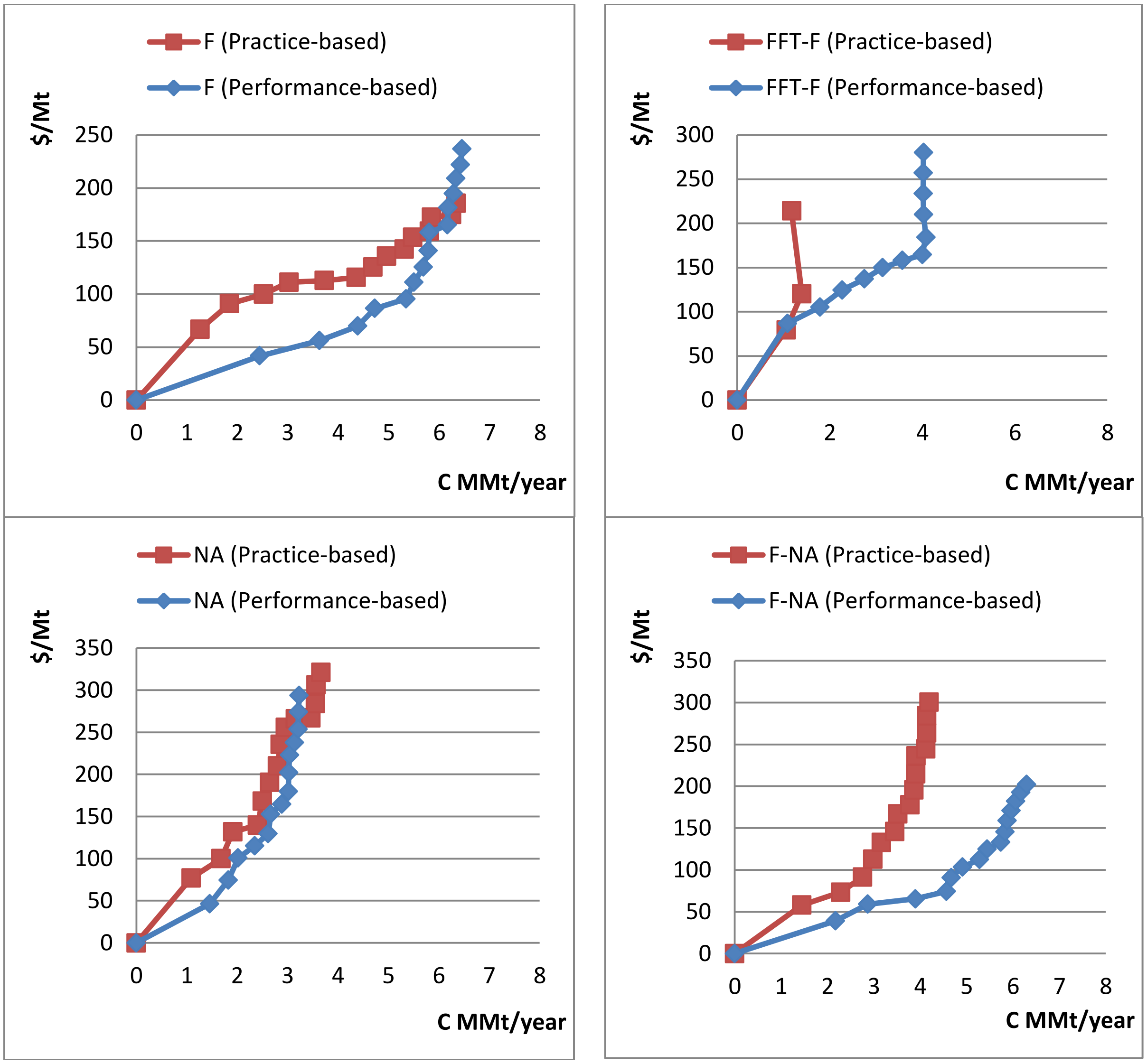
When the landowners are paid for only ‘No activity (NA)’, the adoption rate of the choice ‘NA’ goes up at a decreasing rate as the payment level increases, as shown in Figure A2-c. In Table 5, annual payments to landowners who adopt the choice ‘NA’ with a 10-year contract (from \$10/acre to \$150/acre) lead to annual carbon sequestration ranging from 1.5 MMt to 3.6 MMt. The carbon supply function in Figure 3 shows the total annual carbon sequestration potential of targeting the choice ‘NA’ is 1.3 MMt, 1.9 MMt, and 2.5 MMt, at \$50/Mt, \$100/Mt, and \$150/Mt of carbon price, respectively.

Finally, when landowners are paid an incentive for choosing ‘No Activity’ or ‘Fertilization’ (i.e. payment for ‘F-NA’), as the payment level increases, the choice ‘F’ increases, and the choice ‘FT’ declines drastically (Figure A2-d). Even if the choice ‘NA’ is paid as well, since the carbon sequestration of choice ‘F’ is larger than that of choice ‘NA’, the choice ‘NA’ also converts to the choice ‘F’ as the payment level increases. Thus the trend of annual carbon sequestration along the payment levels in this case is similar to the case of only paying an incentive for the choice ‘F’. In Table 5, the annual payment, ranged from \$10/acre to \$150/acre, for only the duration of the contract to landowners who adopt the choice “F’ or ‘NA’ yield additional carbon sequestration from 2.2 MMt/year to 6.3 MMt. The annual carbon sequestration potential in this region is 2.6 MMt, 4.9 MMt, and 5.8 MMt, at prices of \$50/Mt, \$100/Mt, and \$150/Mt, respectively (Figure 3).

3.5. Practice-Based Payments vs. Performance-Based Payments

In this section, I compare the carbon sequestration potentials in the western US between practice-based payment schemes and performance-based payment schemes with a 10-year contract. Figure 4 shows the annual carbon sequestration potentials in the western US

Figure 4. Additional carbon sequestration with different MPs targetings under different payment scheme (10-year contract)



with four different MP targets under a two payment scheme. Under the practice-based payment scheme, at the price of $50/Mt, the potential of carbon sequestration in the western US ranges from 0.7 MMt to 1.2 MMt depending on the different payment targets. Under the performance-based payment scheme, at the price of $50/Mt, the carbon sequestration potential ranges from 0.7 MMt to 3.9 MMt. Overall, payment only for the choice ‘F’ yields the highest carbon sequestration relative to other MPs under both schemes. The performance-based payment scheme yields higher levels of carbon sequestration than the practice-based payment scheme in almost every incentive payment strategy especially with lower annual payment levels and without considering any measurement and monitoring costs.[22] This is because the lands with higher carbon sequestration potentials are paid more under the performance-based payment scheme.

3.6. Sensitivity analysis

In the econometric and simulation analysis, we use a 5% discount rate to calculate annualized net returns (annual LTV) and incentive payments. We examined the sensitivity of the predicted probability of MP choices and carbon sequestration with alternative discount rates of 3% and 7 %. In calculation of annual LTVs (*AnnLTV*), as the discount rate rises from 3% to 5% and 7%, the annual LTV of each MP becomes lower. In the econometric analysis, as the discount rate becomes higher, the relative magnitude of semi-elasticities of 'FFT' and 'FT' increases (Table 6). This implies that as discount rate changes from low to high, the probability of choosing MPs which allow partial harvest become more responsive.

Table 6. Own semi-elasticities of annual LTVs with different discount rates

Discount rate	FFT (Fertilization & Fuel treatment)	F (Fertilization only)	FT (Fuel treatment only)	NA (No activity)
3%	0.199(0.069)	0.339(0.114)	0.667(0.094)	0.671(0.303)
5%	0.204(0.063)	0.282(0.101)	0.699(0.096)	0.405(0.229)
7%	0.236(0.065)	0.262(0.100)	0.592(0.087)	0.253(0.149)

[22] We didn't consider the measurement and monitoring costs when we compare the cost of carbon between practice-based scheme and performance-based scheme. If we take that into account, the carbon sequestration potential under performance-based approach can be less cost effective than that we estimated, because generally measurement and monitoring cost under performance-based scheme is greater than that under practice-based scheme.

An increase in the discount rate changes the predicted probability of adopting the MPs. As the discount rate increases, the predicted probability of adopting the choices including fuel treatment (the choice FFT and FT) increases by 0.2%. 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 by 0.2 Mt/acre as well.

Table 7. Annual carbon sequestration potential at $100/Mt with different discount rates

	Practice-based payment			Performance-based payment		
Payment Targets	3%	5%	7%	3%	5%	7%
F	1.0	2.5	2.5	4.4	5.4	5.7
FFT-F	0.0	1.2	1.2	0.7	1.6	2.0
NA	1.9	1.7	1.5	2.0	2.0	1.9
F-NA	1.8	2.8	3.5	3.6	4.8	6.1

Suppose we pay incentives to landowners who adopt a certain MP with a 10-year contract. As the discount rate increases, the level of annualized payments also increases. However if the corresponding return elasticities of MPs decreases, the impact of an increase in the discount rate on the adoption rate of MPs and carbon sequestration potential is ambiguous. Table 7 shows the annual carbon sequestration potentials at a carbon price of $100/Mt when the discount rate increases from 3% to 5% and 7%. When the payment targets only the choice ‘F’, as the discount rate increases from 3% to 5% and 7%, the annual carbon sequestration increases from 1 MMt to 2.5 MMt, and 2.5 MMt under practice-based payments, and from 4.4 MMt to 5.4 MMt and 5.7 MMt under performance-based payments. The payments targeting the choice ‘FFT’ or ‘F’ (FFT-F) and the choice ‘F’ or ‘NA’ (F-NA) showed the same trends with targeting only for the choice ‘F’ as well. That is as the discount rate increases the annual carbon sequestration potential increases at the same level of payment. However, in the case of payment targeting for the choice ‘NA’, annual carbon sequestration decreases from 1.9 MMt to 1.7 MMt and 1.5 MMt under practice-based payments and from 2 MMt to 2 MMt and 1.9 MMt under performance-based payments at discount rates of 3%, 5%, and 7%. This is because of the relatively large decrease in own-return semi-elasticity of the choice ‘NA’ as the discount rate increases, which leads to a lower adoption rate of the choice ‘NA’ at a discount rate of 7% relative to 3% and 5% even if the payment level at 7% is relatively high.

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 increases. This induces an increase in the adoption rate of choosing alternative MPs for carbon sequestration, and thus increases annual carbon sequestration potential. However since the annual carbon sequestration rate is decreasing over time, it is ambiguous the impact of an increase in the duration of contract on the cost per unit of carbon under different incentive payment targets and criteria. Note that as the duration of the contract increases, if increasing rate of incentive payments is higher than increasing rate of annual carbon sequestration, the marginal cost of carbon sequestration increases. Our empirical analysis finds that as the duration of contract increases from 5-year to 10-year, average carbon sequestration potential increases given the same level of carbon price (i.e. marginal cost decreases). If the duration of the contract increases from 10 to 15 years, it tends to decrease (i.e. marginal cost increases). For example, as shown in Table 8, at $100/Mt of carbon price, a 10-year contract performs best in annual carbon sequestration in the case of payments targeting ‘F’, and ‘F-NA’. This is because there is a time lag to achieve a certain level of carbon sequestration with the choices ‘F’ and ‘FFT’. Thus a 5-year contract cannot produce as much carbon as a 10-year contract given a level of annual payment. With a 15-year contract, because of the rate decreasing yield of annual carbon sequestration, the marginal cost to produce an additional carbon is higher than with a 10-year contract. However, in the case of payments targeting 'NA', as the duration of the contract increases from 5- to 10- to 15-years, annual carbon sequestration potential decreases at a carbon price of $100/Mt. This is because a large portion of additional carbon sequestration is lost by converting from other MPs to the choice 'NA' as soon as the decision to convert is made. For example, the amount of carbon stored by preventing anticipated thinning for fuel treatment accounts for additional carbon sequestration as soon as the decision is made.[23]

Table 8. Annual carbon sequestration potential with alternative durations of contract at $100/Mt of carbon price

Payment targets	Practice-based payment			Performance-based payment		
	5-year	10-year	15-year	5-year	10-year	15-year
F	1.98	2.96	2.54	3.18	4.77	4.77
FFT-F	0.87	1.07	1.06	1.14	1.79	1.37
NA	1.49	1.61	1.41	2.16	2.06	2.02
F-NA	2.11	2.52	2.47	3.30	4.42	4.12
Average	1.61	2.04	1.87	2.44	3.26	3.07

4. Comparison the results with other studies

It is difficult to compare the results of the carbon sequestration potentials under incentive payments in this study with other study results. The main reason is that there are no comparable previous studies which examine the carbon sequestration potential by managing intermediate practices of forests in response to incentive payments. The created carbon supply functions with four different targeting options are comparable with studies estimating the cost of carbon sequestration through afforestation. However, to compare with the results from other studies, we need to normalize the results by adjusting for discount rates, geographic region, and constant-year dollars. Stavins and Richards (2005) summarized and compared the 11 studies on carbon

[23] Note that we do not consider the carbon flow after the contract is terminated in this study. We only consider the carbon sequestration potential within duration of contract. If it is considered, the results might be changed.

sequestration potentials through afforestation using the normalized carbon supply function. They show that 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 in the US.[24] Since our study covers only the western US region, we scaled up a regional level supply function to the national level by applying our results to 721 million acres of the forestlands in the US. This allows us to compare our results with those of other studies. In our results, the cost of carbon by targeting the option 'F', 'NA', or 'F-NA' ranges from $92/Mt to $210/Mt for 50 MMt of annual carbon sequestration. Only payments targeting option 'F' can achieve 100 MMt of annual carbon sequestration at a carbon price of $155/Mt. Since we take into account only the NIPFs in the western US, it is difficult to directly compare the carbon sequestration potential with an absolute amount; nevertheless, the comparison with the absolute amount of annual carbon sequestration shows incentive payments for intermediate forest MP yields less carbon with a relatively higher cost of carbon than for afforestation, so that the carbon supply function of changing intermediate forest MPs is steeper than that of afforestation. An important implication of this is that changing only intermediate forest MP without extending the rotation period cannot produce as much carbon sequestration as through afforestation, because physical carbon sequestration potential per acre is lower than that with afforestation.

[24] Stavins and Richards (2005) concludes 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.

5. SUMMARY AND CONCLUSION

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 (MPs). This study takes a first step towards filling this void by analyzing the factors affecting NIPF landowners' choice of intermediate forest MPs and examining how these choices might change in response to the use of incentives for carbon sequestration. Additionally, we simulate the carbon sequestration potential for each MP given different incentive payment schemes.

Our results suggest that that the factors affecting the probabilities of adopting intermediate MPs of forests differ by the choice of MPs. The own marginal effects of the probabilities of choosing an MP with respect to expected net returns are all positive and significant, and indicate that an increase in expected net returns of a certain MP increases the probabilities of adopting that MPs. Landowners' demographic characteristics do not significantly affect the probability of choosing a certain MP, while 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 MPs show that the choice of 'Fertilization' or 'No Activity' can sequester more carbon than practices which include 'Fuel Treatment'. This result highlights potential tradeoffs between management objectives, as activities such as fuel treatment which are 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 with different targeting strategies show that targeting the choice of 'Fertilization' yields the highest carbon sequestration potential. Additionally, our results suggest that a performance-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 intermediate MPs 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.

We finally want to highlight that the incentive payment strategies considered in this study only focus on carbon sequestration as an environmental benefit provided through alternative MPs. If the incentive policy targets one or more environmental benefits such as biodiversity, soil erosion, and water quality, our results may not hold and will depend on correlation among the environmental benefits considered.

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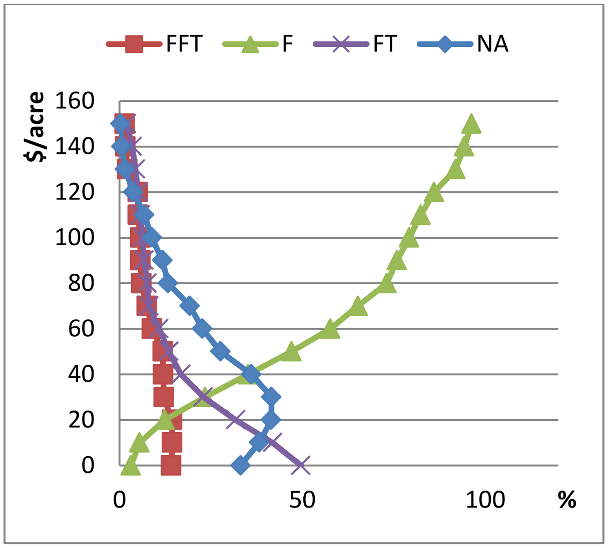
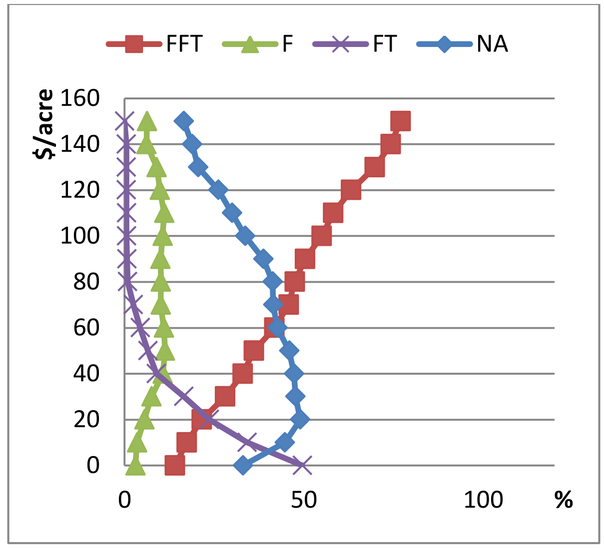
Appendix

Figure A1. Adoption rate under practice-based incentive payment with different MPs strategies

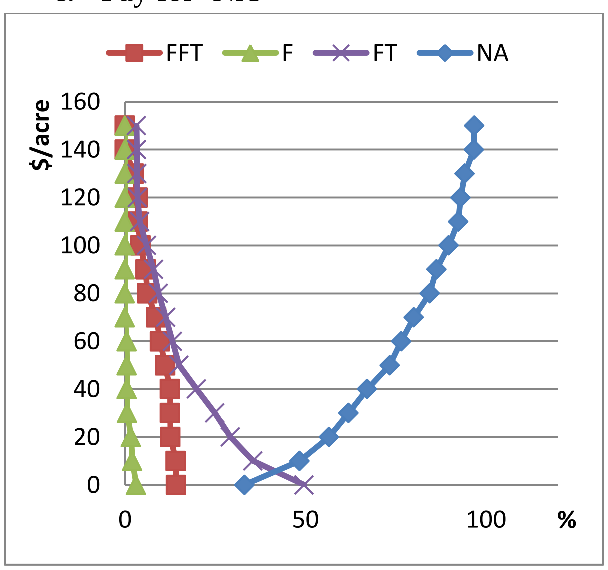
a. Pay only for ‘F’



b. Pay for ‘FFT-F’



c. Pay for ‘NA’



d. Pay for ‘F-NA’

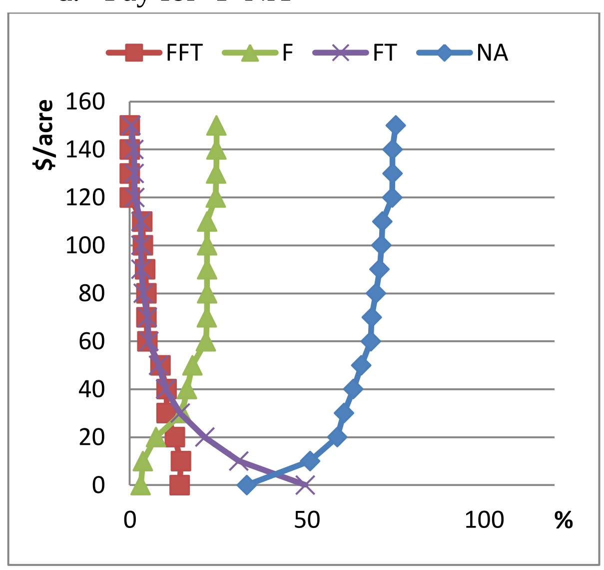
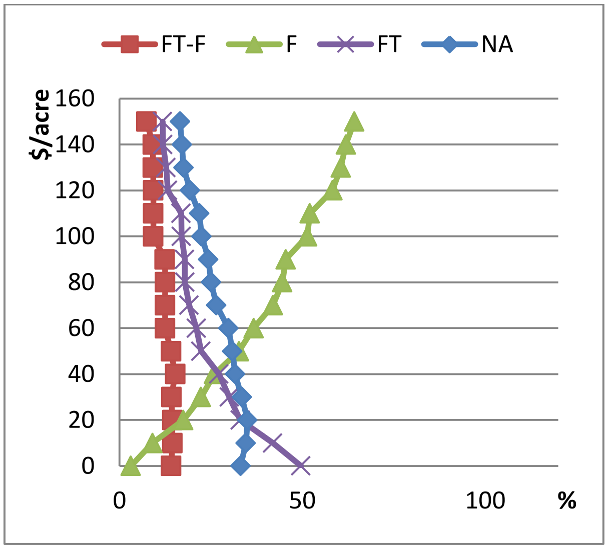
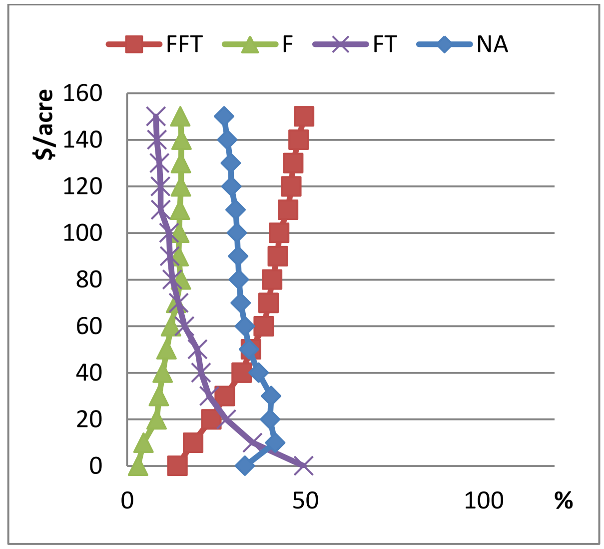


Figure A2. Adoption rate under performance-based incentive payment with different MPs strategies

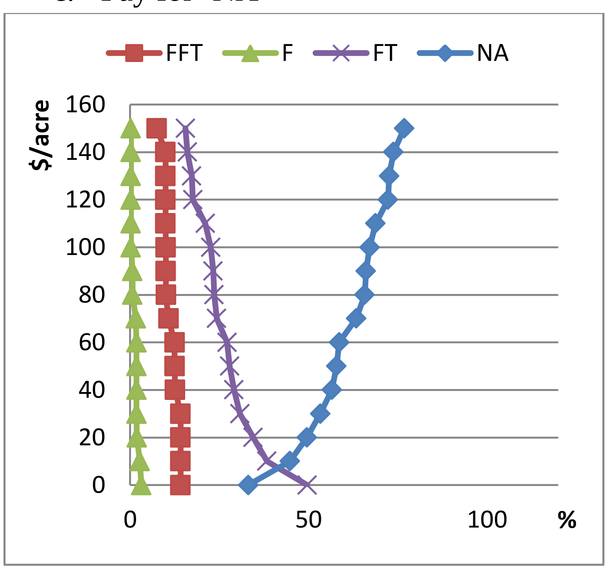
a. Pay only for 'F'



b. Pay for 'FFT-F'



c. Pay for 'NA'



d. Pay for 'F-NA'