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Evaluating land-use and private forest management responses to a potential forest carbon offset sales program in western Oregon (USA)

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ABSTRACT

We describe the use of linked land-use and forest sector models to simulate the effects of carbon offset sales on private forest owners' land-use and forest management decisions in western Oregon (USA). Our work focuses on forest management decisions rather than afforestation, allows full forest sector price adjustment to land-use changes, and incorporates time-dependent costs and restrictions of offset programs. The land-use model utilizes structure count data on some 21,000 plots spanning 30 years. The intertemporal optimizing forest sector model employs mill-level demand and FIA plot-level inventory. Our linked simulation modeling projects that an offset sales program could reduce forest land loss to development in western Oregon by about 4700 acres over the 2010–2060 simulation period for each $1 increase in the carbon price. At $10 per tonne CO_2, regional private carbon stocks would be roughly stabilized at current levels over the period to 2060. Rotations would lengthen on enrolled lands, as expected, but use of planting, thinning and uneven-aged management would decline.

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1. Introduction

Policymakers and the concerned public have emphasized the need for carbon emission mitigation programs to address climate change resulting from global use of fossil fuels (Metz et al., 2007). Among proposed approaches, carbon markets and carbon offsets have received significant attention. Carbon markets would establish and sell a supply of tradable emission permits, allowing industrial users of fossil fuels to emit a set amount of CO_2 as defined by the permits held. A forest carbon offset program would allow forest landowners to sell carbon emission permits in return for altering their forest area and/or its management in ways to sequester and store additional carbon. Carbon offset sales are of particular interest among forest policymakers because they would, in theory, provide financial incentives to owners to retain land in forest cover rather than convert it to non-forest and developed uses with attendant losses of an array of ecosystem services (Collins and Larry, 2007). The extent to which forest carbon offset sales programs would actually slow land shifts from forest to non-forest uses depends on the array of development opportunities available and the degree to which private landowners would respond to an offset sales program in their land-use and forest management decisions (Kline et al., 2009).

This research links land-use and forest sector models to simulate the effects of forest carbon offset sales on private forest owners' land-use and forest management decisions in western Oregon (USA). In this region, land shifts between agriculture and forestry have been minimal for the past several decades. As a result adaptation to an offset sales program will likely involve adjustments in rates of forest land shifted to development and changes in forest management practices. We simulate a hypothetical offset sales program that is similar in broad form to the Climate Action Reserve protocol (Climate Action Reserve, 2012). The analysis provides estimates of potential land-use trends (shifts of forest to developed uses), silvicultural decisions (including harvest age), timber stocks and harvest, and carbon offset supply outcomes in response to alternative carbon prices in the sales program.

2. Departures from previous studies

Richards and Stokes (2004), van Kooten et al. (2004) and Stavins and Richards (2005) provide excellent reviews of past studies of the costs and impacts of forest carbon offset sales (or carbon tax/subsidy) programs. Following Richards and Stokes (2004), these studies can be divided into engineering approaches, econometric land-use models, and forest-agriculture sector simulators. Engineering studies (e.g., Moulton and Richards, 1990; Parks and Hardie, 1995) develop, in effect, comparative cost evaluations of alternative carbon sequestration projects in forestry and/or agriculture. While they have been used to examine afforestation options on agricultural land, they do not provide a way for considering land use competition with development.

Applied econometric land-use models employ historical land-use data in empirical specifications derived from rent maximizing behavior

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to explain shifts in land among classes of use (e.g., Plantinga et al., 1999; Lubowski et al., 2006). Assuming that land-use responses to carbon offset revenues will be the same as historical responses to land rent changes (without carbon markets), land rents are adjusted by offset sales revenues and new land-use patterns (with associated carbon flux changes) are projected. Land use change is voluntary from a landowner's perspective in this context, and the models distill landowners' “revealed preferences” (e.g., Newell and Stavins, 2000). These studies model only afforestation and deforestation options and most have used highly simplified biological representations of the forest resource. Some have considered product price feedback to land rents in an approximate form (Lubowski et al., 2006, appendix A). Offset sales programs have generally been simulated as tax or subsidy payments and without formal treatment of the distinct contract costs and restrictions of such programs.

Forestry-agriculture sector models (e.g., Adams et al., 1999; Sohngen and Mendelsohn, 2003) employ the strong assumption of market surplus maximization to project land-use and production decisions in the two sectors where some portion of the joint land base can be employed in both forestry and agriculture. Land-use decisions are made to maximize land rents, given prices, costs and discount rate. With the exception of Latta et al. (2011), past approaches have treated enrollment as mandatory and not as a function of relative rent impacts. Land loss to urban and developed uses is generally treated as exogenous and invariant with rents in the endogenous sectors. Most models have employed some detail in the projection of forest growth and have addressed program responses in the management of existing stands and through afforestation and deforestation. Sector product price and output feedbacks on land rents are endogenous in these models. Offset sales programs have generally been highly simplified.

To simulate the reaction of land-use decisions to an offset sales program, we integrated elements of previous work using econometric land-use and sector models. The dominant land-use shifts in western Oregon are from forestry and agriculture to development, while forestry-agriculture land exchange is very limited. Changes in forest management (including rotation age) could be an important form of adjustment to offset sales. Accordingly, we viewed silvicultural options (regeneration, harvest form and timing) as important behavioral responses to carbon offset programs. And, since the short-term derived demand for logs and stumpage is estimated to be highly inelastic in western Oregon (Adams et al., 2002), we also considered product-price feedback to land rents as potentially important. The coupled land-use and forest sector model developed for this study extends past work in three ways: (i) it develops an equilibrium linkage of land-use and forestry production decisions including product price and land rent feedback; (ii) it employs a detailed land-use data base to model land shifts to development at the sub-county level; and (iii) entry into the offset sales program is voluntary and key details of the program are explicitly recognized, including time-dependent costs of participation and use-change restrictions arising from “permanence” constraints typical in program contracts.

3. Land-use model

Following work by Kline (2003) and Kline et al. (2003), we focus on the conversion of forest and agricultural land to developed uses, which is the predominant land-use change observed in western Oregon. Although conversions of land between forest and agricultural uses are possible, they are rare. Forest to agriculture conversions between 1974 and 2009, for example, totaled just 9000 acres for the entire state relative to a non-federal land base of nearly 29 million acres, with just 3000 acres of agricultural land converting to forest (Lettman et al., 2011: 53). Stability between forest and agricultural land uses in western Oregon owes largely to the unsuitability of remaining forest land for agriculture due to soils and topography, and the high rent-earning capacity of lands currently in agricultural uses relative to forestry.

Consistent with previous studies of undeveloped to developed land conversions, we assume landowners are land rent maximizers (Bockstael, 1996; Kline, 2003; Irwin et al., 2009; Irwin and Wrenn, 2014). Forest and agricultural landowners face a range of development opportunities regarding new housing, businesses, and industry. Their decisions among these opportunities are influenced by potential future rents to be earned from development relative to rents earned from forestry and agricultural uses. Rent maximizing decisions and the extent to which new buildings are observed are potentially restricted, however, by local zoning limitations and by topographic characteristics that affect the suitability of lands for development.

We used historical data on building count changes spanning three 10-year time periods (1974 to 1984; 1984 to 1994; 1994 to 2005) compiled by the Oregon Department of Forestry and USDA Forest Service using photo-interpretation of a systematic-random grid of sample points (Lettman et al., 2011). The data consist of 21,008 geo-referenced observations of building counts per 80 acres (80-acre circular areas centered on points) observed on non-federal lands at a sampling density of one point per 462 acres. A subset of these sample points includes detailed forest vegetation survey data (the FIA Forest Survey plots), which were used to develop the biological growth representation in the forest sector model.

Recognizing the importance of these multiple factors, we posit that owners pursue building construction over time on each sample plot so as to maximize expected land rents subject to restrictions of zoning ordinances and plot physiography. We employ a count regression model (Greene, 2012) to model empirically building counts over time. The dependent variable of our land-use model is an integer count of the change in number of buildings over each time interval (1974 to 1984, 1984 to 1994, and 1994 to 2005). Explanatory variables are agricultural and forestry returns (rents), a gravity index as a proxy for urban rents, baseline (1974, 1984, and 1994) measures of building counts, plot slope and elevation, zoning variables (developed, forest, and agriculture) to control for spatial and temporal variation in land-use zoning under Oregon's statewide system of land-use planning, and fixed effects

Table 1
Descriptions and means of the explanatory variables used in the land-use model describing forest and agricultural land development.

Variable	Description	Mean
GRAVITY INDEX	Gravity index computed at the beginning of each time-period (times 1/100,000).	1.496
BUILDINGS	Number of buildings within an 80-acre circle surrounding photo point at the beginning of each time-period (times 1/100).	0.017
SLOPE	Mean slope of the 80-acre circle surrounding the photo point (times 1/100).	0.119
ELEVATION	Mean elevation (meters) of the 80-acre circle surrounding the photo point.	0.349
DEVELOP ZONE	Percent of 80-acre circle surrounding the photo point zoned for development times the proportion of time-period with zoning law in effect (times 1/100).	0.035
AGRI ZONE	Percent of 80-acre circle surrounding the photo point zoned for agricultural use times the proportion of time-period with zoning law in effect (times 1/100).	0.153
FOREST ZONE	Percent of 80-acre circle surrounding the photo point zoned for forest use times the proportion of time-period with zoning law in effect (times 1/100).	0.266
AGRI RETURN	Net present value return in agricultural use measured in $ per acre (times 1/1000).	1.147
FOREST RETURN	Net present value return in forest use measured in $ per acre (times 1/1000) (SEV value).	0.466
DUMMY 1984	Variable equals 1 if observation describes building count change from 1984 to 1994; 0 otherwise.	0.333
DUMMY 1994	Variable equals 1 if observation describes building count change from 1994 to 2005; 0 otherwise.	0.332

Note: The full sample ($n = 60{,}745$) derives from 20,317 points in western Oregon tracked over 3 time-periods. Although a majority of points (21,008) were represented in all 3 time-periods, some were not. The panel thus is unbalanced.

dummies for time period (refer to Table 1 for the names, detailed definitions, and mean values of the explanatory variables).

Following Kline et al. (2003), we included a GRAVITY INDEX variable to represent each observation's proximity to a set of 45 cities and their population computed for plot i as:

$$\text{GRAVITY INDEX}_i = \sum_{j=1}^{K} \text{Population}_j * \frac{96,560.64 - \text{Distance}_{ij}}{96,560.64},$$

where K represents the total number of cities within 96,560.64 m (60 miles) of each sample observation i, Population_j is the US Census Bureau decadal population count of community j closest to the base year, and Distance_{ij} is the distance from the sample point (i) to the centroid of a given community (j) measured in meters. We updated the index over time to account for changing population in the study region.

We used ARCGIS to calculate building counts over time (BUILDINGS), mean slope (SLOPE), and elevation (ELEVATION). In addition, we also developed a spatial time series of zoning policies in place to account for changing development restrictions over time (DEVELOP ZONE, AGRI ZONE, and FOREST ZONE). The Oregon Department of Forestry provided the base GIS layers for these calculations. Calculations followed prior work completed using the building count data (Kline, 2003). Agricultural returns (AGRI RETURNS) were assigned to each observation point using county-level estimates developed by Lubowski (2002). Forest returns (FOREST RETURN) were based on forest inventory plot-level estimates derived by Latta and Montgomery (2004) and used in Montgomery et al. (2006), with returns assigned to observation points based on physical proximity to the nearest forest inventory plot.

We considered a variety of alternative count regression models and model specifications (e.g., hurdle model), as well as the potential for linking resulting model predictions to the forest sector model. Although we also recognized the potential for spatially correlated residuals due to unobserved factors, we did not attempt to account for such patterns in our model. However, our inclusion of several spatial variables in the model collectively helps to counter any spatial dependence issues. In addition, we examined the dependent, independent, predicted, and residual terms in ARCGIS. Dispersion test-statistic results and goodness of fit statistics favored a parsimonious negative binomial specification.

The final negative binomial count regression is statistically significant based on global fit tests (Chi-square = 54,170.30, Pr(Chi-square > cv) < 0.0001; McFadden Pseudo R-squared = 0.43) (see Table 2 for parameter estimates). All of the parameter estimates are significant at the 0.01 level and their signs match prior findings (Kline, 2003; Kline et al., 2003). Overall, the results reveal strong patterns in building activity — patterns consistent with economic theory. Notably, higher rents to agricultural (AGRI RETURN) and forest (FOREST RETURN) land uses are correlated with lower levels of building activity.

Table 2
Negative binomial model for building count data (see Table 1 for variable definitions and sample averages).

Variable	Estimated coefficient (β)	β/Std error
Constant	0.331	5.907
GRAVITY INDEX	−0.213	−8.258
GRAVITY INDEX^2	0.056	13.098
BUILDINGS	18.116	46.231
BUILDINGS^2	−15.437	−47.214
SLOPE	−7.527	−33.171
ELEVATION	−1.213	−20.559
DEVELOP ZONE	1.769	29.163
AGRI ZONE	−0.608	−11.788
FOREST ZONE	−0.482	−8.796
DUMMY 1984	−0.384	−14.605
DUMMY 1994	−0.191	−3.982
AGRI RETURN	−0.317	−9.754
FOREST RETURN	−0.513	−15.866
Alpha	4.787	63.148
lnL	−35,948.27	
AIC	1.184	
BIC	1.186	
N	60,745	

We used the land-use model results to simulate future changes in building counts over 10-year time periods from 2015 to 2105. Simulations were based on updated (or projected) values of the land rent proxy variables GRAVITY INDEX and FOREST RETURN, with all other explanatory variables held constant. Given the near absence of agriculture to forest land use conversions in recent decades and the dataset, we felt that any future changes in agricultural returns over time were more likely to effect changes in the types of agricultural production than to induce conversions of agricultural land to forest use followed by subsequent enrollment in a carbon offset program. Thus, we also held AGRI RETURN constant in our simulations of forestry uses.

The GRAVITY INDEX was updated using county-level population forecasts from Oregon's Office of Economic Analysis (2013). Population forecasts beyond 2040 were created assuming constant population growth rates within counties. Estimates of future values for FOREST RETURN were updated at each simulation time step using outputs from the forest sector model through a joint solution approach (described below). As the predicted building counts were assembled, an updated estimate of the forest land base was generated by removing all lands with more than one building per 10 acres from the initial forest land base. This latter assumption is consistent with previous western Oregon landscape analyses (Johnson et al., 2007; Spies et al., 2007). Once the number of buildings increased above eight—an average of one building per 10 acres—the observation point was assumed to be effectively converted to a developed use owing to the small parcel size.

4. Forest sector model

The forest sector model employs a dynamic, spatial equilibrium approach focusing on the markets for softwood logs and carbon offsets (Adams and Latta, 2005; Montgomery et al., 2006; Adams and Latta, 2007; Im et al., 2007). Unlike past studies, this model provides detail on silvicultural decisions and explicit projections of changes in forest land rents over time. Log demand derives from input requirements of lumber and plywood producers, log supply from both private and public timberlands. The model determines the market clearing log quantities and prices and areas enrolled in the offset sales program over the projection period (100 years in 5-year intervals) by maximizing the discounted sum of producers' and consumers' surpluses (at a real discount rate of 6%).[1] Constraints on the optimization describe the biological dynamics of the timber resource, capacity in lumber and plywood mills, log flows from producers to consuming mills, and carbon stocks (see Appendix for a mathematical outline of the model).

Decision (control) variables include management regime and harvest timings for all existing and regenerated private plots over time (including the areas that elect to participate in a carbon offset program and those that do not), levels of carbon offset sales or credits, timber harvest and intra-regional shipments of logs, and changes in mill capacity over time. The price of an additional unit of harvest (stumpage) is the shadow price of the harvest equation (Appendix Eq. (A5)). The price of an additional unit of volume delivered to a mill (log price) is the shadow price of the log demand Eq. (A6). The price of an additional unit of bare timberland, the soil expectation value or land rent, is the

[1] The effective interest rate for nonindustrial owners is less than 6% in our analysis. As described in Im et al. (2007) our model recognizes that non-industrial owners manage for both market and non-market returns. This results in an inventory age class structure with significantly more area in older age classes than found on industrial ownerships. To reflect these preferences, constraints require the proportions of projected nonindustrial forests in older ages to meet or exceed the historical observed acreages in these ages. This limitation is equivalent to optimization of the present net worth objective at a lower discount rate (see, for example, Gan et al., 2001).

shadow price of constraint (Eq. (A3)). Since our model is effectively a "model II" using Johnson and Scheurman's (1977) terminology, the price of an additional unit of bare timberland, the soil expectation value or land rent, is the shadow price of constraint (Eq. (A3)).[2] The capacity adjustment mechanism is defined in Eqs. (A7) and (A8). Calculation of the creditable carbon flux under the offset sales program is carried out in Eq. (A9).

The timber inventory was modeled using data derived from the USDA Forest Service's annual measurement of permanent plots on western Oregon forest land (Donnegan et al., 2008) for the years 2001–2009. Industrial and non-industrial private ownership classes are recognized. For both owner classes, available silvicultural practices in existing stands included pre-commercial thinning, commercial thinning, and three partial cutting (non-clearcut) regimes representing decreasing levels of post-harvest residual stocking. In regenerated stands, the level of regeneration intensity and the use of thinning can be varied. Choices among possible harvest timings and use of the clearcut or partial cutting regimes are endogenous for each plot (for details, see Adams et al., 2002).

Projections of current and future inventory volumes and stand characteristics for all plots and management regimes were derived from the UDSA Forest Service's Forest Vegetation Simulator (FVS) stand projection system (Dixon, 2002). FVS is a distance-independent individual tree growth model that projects height and diameter growth, crown recession and mortality for each live tree in the inventory plot records as a function of various stand characteristics, including proxies for inter-tree competition. In the partial cutting regimes, growth and mortality respond to changes in stand characteristics and competition in varying degrees depending on the extent of removals in a given regime. These regimes comprise a series of thinnings with alternative intensities and timing and have no specific rotation or stand replacement point. Thus regeneration beneath the over-story is not considered.

The small volumes of log flows from public ownerships allowed under current policies are taken as exogenous and insensitive to price. They do not vary in the current analysis.

Western Oregon log demand was estimated using a normalized, restricted quadratic profit function then disaggregated to individual mills or milling centers. The mills were assumed to have a single output (lumber or plywood), with residues treated as fixed proportion by-products. Inputs include logs, labor and other variable factors. Capital stock (measured here as the maximum physical log processing capacity) is treated as quasi-fixed in the short-term (1–5 years) and technology is represented by a time trend.[3]

We assume that mill-level capacity may change in the long-term (between 5-year periods), shifting both the log demand equation (hence market surplus) and the capacity bounds on log demand (Eq. (A7)). Over time capacity follows the usual inventory identity (A8). Basic maintenance and repair, at a charge, are required on all capacity ($\text{Maintenance}^{(i)}_{\text{MILLS}}$). Investment in new capacity to expand output beyond current levels ($\text{Expansion}^{(i)}_{\text{MILLS}}$) is also possible. Costs of both actions on capacity are assessed in the objective [the "Capacity costs" term in (Eq. (A1))]. In this process, capacity is determined so as to maximize the present value of its net returns over the projection period.

5. Carbon accounting and offsets

Carbon accounting is comprised of: (i) a model that determines the carbon stocks and fluxes of the forest resource, and (ii) a methodology for determining the level of offsets available for sale. Carbon storage in a stand is composed of six pools: merchantable live tree, non-merchantable live tree, below ground live, below ground dead, standing and downed woody debris, and forest floor shrubs, herbs, litter and duff carbon. For each plot, biomass and change in carbon stocks were computed using the Fire and Fuel Extension of FVS (Rebain, 2010).

Carbon offsets are determined by the activities of forest landowners. To date "Improved Forest Management" (IFM) projects—as opposed to afforestation—have represented a relatively small share of total offset supply in voluntary carbon markets. This has changed with the recent acceptance by three primary US registries—Climate Action Reserve (CAR), Verified Carbon Standard (VCS), and American Carbon Registry (ACR)[4]—of methodologies for use in determining IFM offset allocations. In each registry, methodology describes which carbon pools are counted, the benchmark against which change is to be measured, the length of the required time commitment (permanence), and the extent to which harvested wood products are counted for (and against) emissions reductions.

The offset calculation methodology used in the current study follows the CAR approach with simplifications to fit within the market model framework. The provisions of this simplified protocol are:

(1) Offsets (Appendix Eq. (A9)) are based solely on the three live tree pools (as noted above): merchantable, non-merchantable, and below ground.
(2) All IFM methodologies include a baseline level of carbon sequestration against which change can be determined. In the current approach, offsets are not awarded after initial enrollment until stocks per unit area exceed regional forest inventory averages.
(3) Landowners can harvest timber at any time but must pay back to the sales program the value of the carbon emitted through harvest, including on and off site losses, at time of harvest. Payments for carbon in regenerated stands after harvest begin as soon as measureable carbon can be counted on the site. We do not impose the regional baseline level as a lower bound for receipt of payments for regenerated stands.
(4) An area enrolled in the carbon offset program must remain enrolled for 100 years.
(5) The decision to enroll is made in the 2010 period only, with no enrollment allowed in subsequent periods. This eliminates the possibility of enrollment in the program following an untaxed harvesting emission (which is not allowed under CAR unless the land has changed ownership).
(6) We follow CAR guidelines in the treatment of emissions from non-merchantable carbon left on a plot after harvest and from merchantable material converted to products.
(7) We also use CAR's requirement of a 20% deduction in harvested wood products carbon for leakage.

Unlike most past studies of forest carbon offsets, estimates of the "operating" costs of participating in the offset sales program are explicitly recognized. These include both project establishment costs, such as inventorying the stand and verification, and annual and periodic costs of monitoring and verifying a project once established. Costs derive from the "average" parcel size in Galik et al. (2012) and vary over time with projected plot conditions.

6. Linking land-use and forest sector models

The market model employs 1300 Forest Service FIA forest land plots (each representing roughly 7000 acres), while the land-use model uses data from roughly 21,000 building count photo points. To bridge this spatial scale gap, a map-based approximation method was used in which forest inventory plots located nearest to existing urban areas

[2] Johnson and Scheurman (1977) demonstrate this using Kuhn–Tucker conditions for the discrete time case and Sohngen and Sedjo (1998) for a continuous time model.

[3] Estimation details, results and data are available from the authors on request.

[4] CAR, http://www.climateactionreserve.org/how/protocols/forest/dev/version-3-3/; VCS, http://www.v-c-s.org/sites/v-c-s.org/files/AFOLU%20Requirements%2C%20v3.4.pdf; ACR, http://americancarbonregistry.org/carbon-accounting/standards-methodologies/improved-forest-management-ifm-methodology-for-increased-forest-carbon-sequestration-on-u-s-timberlands. All sites last visited on 6 March 2015.

were assumed to be developed first, consistent with development patterns found to be prevalent under Oregon's land use planning program (Kline, 2005).

The land-use and forest sector models share common endogenous variables, forest land area and land rents, whose values are necessary for model projections. We employed an iterative Gauss–Seidel approach, sometimes called "soft-link" (Messner and Schrattenholzer, 2000; Tavoni et al., 2007), to solve this simultaneous system of separate but interdependent models. The land-use model was first solved using a trial set of future forest land rents over 100 years. The resulting forest area losses to development were transferred to the forest sector model and a revised market projection with land rents developed. These rents were, in turn, used in the land-use model to generate a revised set of development losses and the process continued until changes in the forest land area losses between one iteration and the next were less than 1%.

7. Results

The land-use and forest sector models were solved for twenty 5-year periods, simulating carbon price scenarios ranging from $0 to $50 per tonne CO_2. In the discussion that follows we focus on the first 50 years of the projection. We consider this time-period as the most relevant for current policy decisions.

7.1. Land-use changes

As carbon prices rise, less forest land is shifted to developed uses, avoiding deforestation and raising the average forest carbon stock on private lands (Fig. 1). Forest area loss (total for 2010–2060) declines from about 409,000 acres in the base to just under 166,000 acres at $50 per tonne CO_2. Averaged over all scenarios, about 4700 acres of deforestation is avoided for each $1 increase in CO_2 price. As shown in Fig. 2, base case forest land area losses are concentrated in the Portland Metro and Medford-Grants Pass areas of western Oregon, continuing historical trends. This general pattern of development distribution does not change with the advent of the carbon sales program and higher forest land prices.

At lower CO_2 prices, rates of forest land loss to development are variable over time, with notable increases in acres shifted from forest to developed uses occurring from 2020 to 2025 and from 2040 to 2045 (Fig. 3). The timing of these increases is due partly to the threshold nature of our land-use forecasts, where conversion of forest land to development is based on achieving a minimum structure count. Additionally, the higher level of forest land loss between 2020 and 2025 owes in part to the relatively significant absolute increase in population anticipated between 2020 and 2025 compared to other periods. Population increases

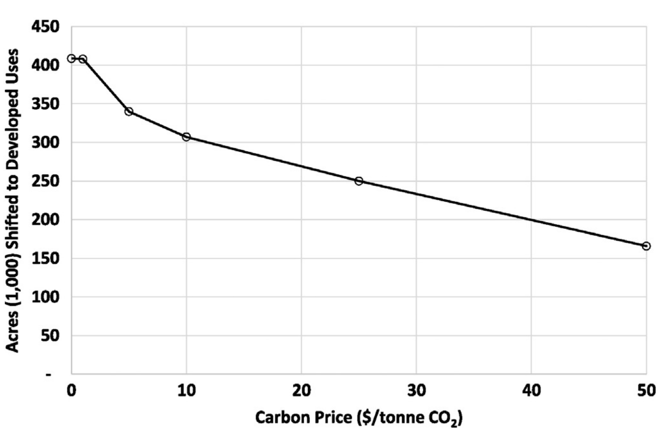

Fig. 1. Projected total loss of private forest land to developed uses from 2010 to 2060 by carbon sales price in western Oregon.

are a key factor driving increased development in our land-use forecasts. More generally, as carbon sales prices rise, they reduce total forest land losses and slow future rates of loss, as seen by the growing gap between the base and non-zero carbon price cases (Fig. 3).

7.2. Program enrollment

Rising carbon prices attract increasing areas of forest land into the carbon offset sales program (Table 3). More than one-third of the private forest base is enrolled at $10 per tonne CO_2 and nearly half at $25 per tonne. The projections also indicate that acres enrolled are drawn from across the range of forest productivity or site quality classes, roughly in proportion to their occurrence in the current inventory. Higher productivity forest lands are concentrated at lower elevations and on the margins of agricultural areas in the Willamette Valley, where their proximity to urban areas would entail greater competition from development uses. Our results suggest that a carbon sales program would not necessarily shift these (higher productivity) lands into carbon contract (100 year commitment) status in greater proportions than more remote (lower quality) sites.

7.3. Forest management

Forest land enrolled in the offset sales program is shifted into different types of management compared to non-enrolled land, significantly lengthening rotation ages consistent with findings of past single-stand studies (e.g., van Kooten et al., 1995). In terms of silvicultural treatments, the general influence of the carbon sales program on enrolled acres is to simplify management and reduce partial harvest treatments (commercial thinning and uneven-aged regimes) with their associated near-term carbon emission charges. In the base case (at $0 per tonne CO_2), about 84% of existing stands are managed in a "grow only" form with no treatments before clearcut harvesting, 10% receive some form of commercial thinning and the remaining 6% employ an uneven-aged regime (with no clearcut). Under the carbon sales program, enrolled existing stands do not use uneven-aged regimes and commercial thinning is applied to only 4% of the stands at the $50 per tonne CO_2. In enrolled stands that are harvested and regenerated, management allocations shift toward "plant only" regimes (plant with no other treatment prior to clearcut) as carbon prices rise, with less than 5% of the enrolled acres in any other regime at $50 per tonne CO_2.

On forest land that is not enrolled in the carbon sales program, the application of uneven-aged regimes in existing stands also declines. Non-enrolled stands that are harvested and regenerated continue to apply the full range of silvicultural regimes with the area allowed to regenerate naturally after harvest doubling at $50 per tonne CO_2. Thinning in either natural or planted stands occurs in two-thirds of all stands, as a means of accessing harvestable volume earlier in the rotation.

In the base case (with no offset sales program), the average age of harvest for stands existing at the start of the simulation is roughly 54 years, while stands harvested and regenerated after the start of the projection are cut (in the "second" rotation) at an average of 44 years. Under a carbon sales program, the average harvest age for enrolled existing stands is 7 to 19 years older than the base case and 1 to 17 years older for enrolled stands that are cut and regenerated. At the same time the area of enrolled lands that is not harvested at all over the projection grows as carbon price rises (see similar single-stand theoretical results in van Kooten et al., 1995). At $5 per tonne CO_2, 15% of the enrolled acres remain unharvested through the simulation period, rising to 32% at $25 per tonne and to nearly 60% at $50 per tonne. Thus, the effective rotation impact of the carbon sales program on areas enrolled is substantially greater than suggested by average harvest ages alone.

For non-enrolled lands, the average harvest age of existing stands falls gradually with the carbon price as log prices rise and these lands are managed more intensively to replace harvest volumes lost to the

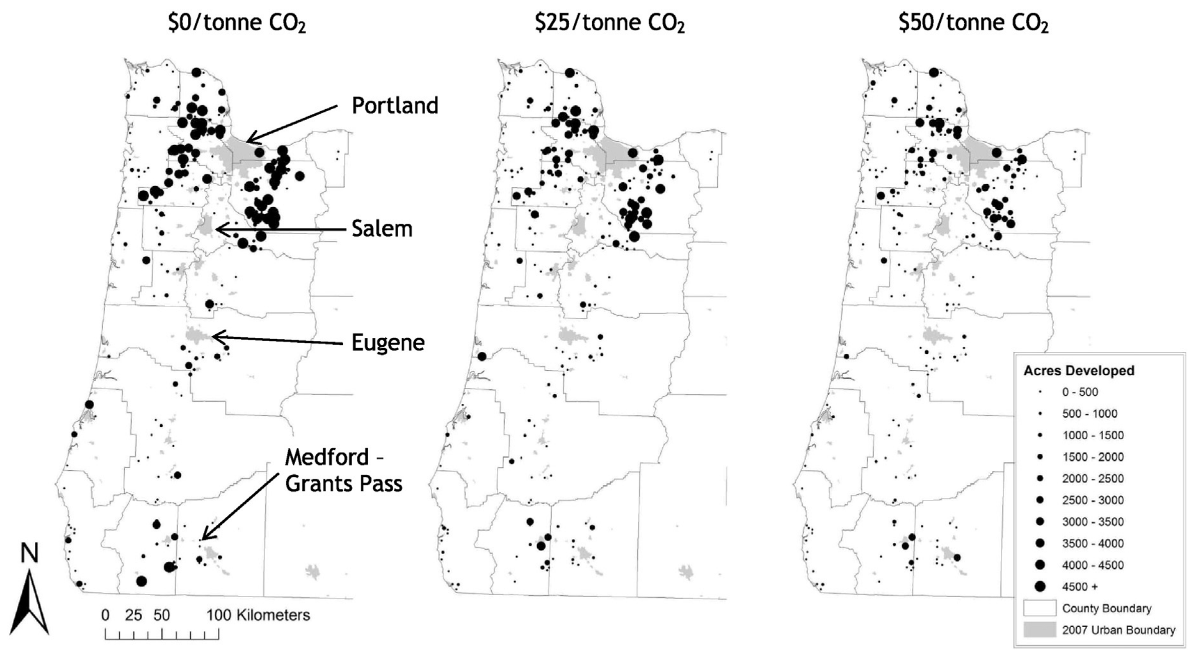

Fig. 2. Concentrations of land use change from forestry to development in western Oregon, total area 2010–2060 by CO_2 price.

carbon sales program. For example, the rotation at $50 per tonne CO_2 is about 5 years shorter than the base case.

7.4. Carbon stocks

Stocks of live tree carbon on private timberlands fall slightly in the base case as land value maximization objectives motivate continued reduction in timber stocks (Fig. 4). At $10 per tonne CO_2, private carbon stocks would be roughly stabilized and at $50 per tonne more than triple by 2060. This latter result is not surprising given the large fraction of enrolled acres that are not harvested over the simulation period.

Carbon flux behavior differs markedly between lands enrolled in the offset sales program and those that are not enrolled. The average net "leakage"—the difference between carbon flux gains on enrolled areas and losses on lands not enrolled—varies markedly by carbon price. Discounting and cumulating periodic flux increments and reductions over the 2010–2060 period, we can compute the ratio of flux losses to flux gains (last column of Table 3). At $1 per tonne CO_2, 95% of the discounted flux increment due to the COSP is offset by flux reductions on non-enrolled lands. But at $10 per tonne CO_2, leakage falls to 54%, and at $50 losses decline to only 5% of increments.

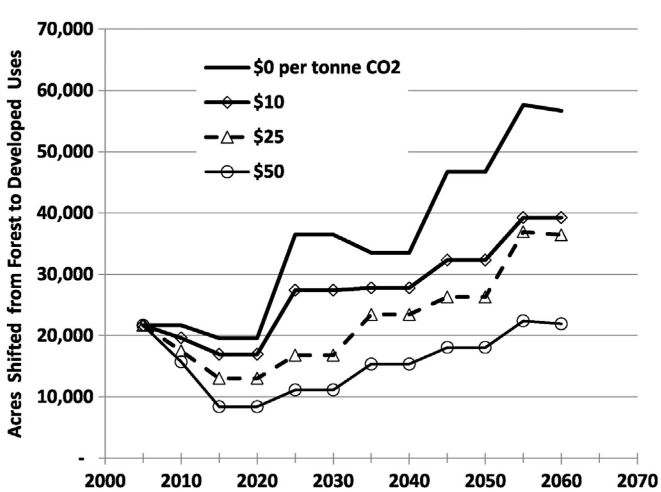

Fig. 3. Projected land loss from private forest to developed uses per period to 2060 in western Oregon by simulated CO_2 price.

7.5. Log market impacts

Timber harvest falls as CO_2 prices rise, consistent with theoretical expectations (Fig. 5). At CO_2 prices between $10 and $50 per tonne, harvest derives in varying proportions from lands enrolled and not enrolled in the offset sales program. The spread is not great, however, and does not change consistently with carbon price, ranging between roughly 50% (in):50% (out) at $10 per tonne CO_2 to 57% (in):43% (out) at $25 per tonne. Inventory impacts (consistent with carbon stock results) are fairly dramatic at higher carbon prices, doubling the base case level by 2060 at $25 per tonne CO_2 and more than tripling at $50 per tonne.

8. Discussion and conclusions

Combining land-use and forest sector models for western Oregon, this study simulated land-use and forest management responses to a potential CO_2 offset sales program patterned after the California CAR program. Unlike some past studies, our joint model recognizes the voluntary nature of the offset sales program and the influence of transaction costs. Integration of the two models also allows full, contemporaneous feedback between forest management and land-use decisions: forest land values depend on expected future returns to forestry and

Table 3
Area of western Oregon private forest land enrolled and not enrolled in carbon offset sales program and carbon flux loss relative to gain at various CO_2 prices.

CO_2 price ($/mt)	Acres enrolled in carbon program	Acres not enrolled in carbon program	Percent of total land base enrolled	Carbon flux loss[a] as percent of flux increment
0	0	6,469,550	0%	
1	334,552	6,134,999	5%	95%
5	1,845,675	4,623,875	29%	70%
10	2,390,395	4,079,155	37%	54%
25	3,100,907	3,368,643	48%	19%
50	3,440,477	3,029,073	53%	5%

[a] Discounted 2010–2060 carbon flux loss on non-enrolled forest lands relative to discounted flux gain on enrolled lands.

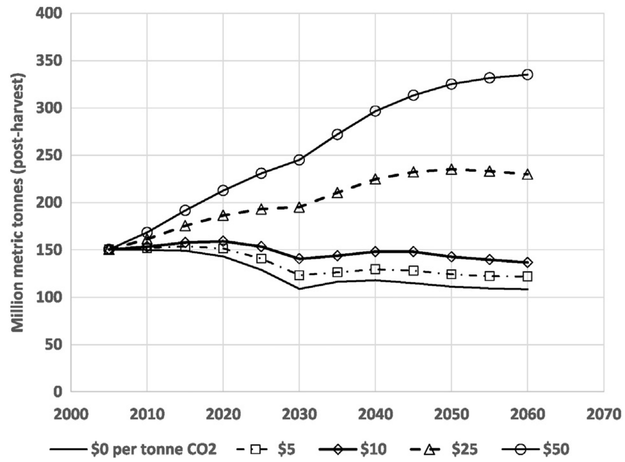

Fig. 4. Live tree carbon (not discounted) on all private lands in western Oregon by carbon price.

forestry returns depend in part on the area of land available for forest production. Actual land and forest product markets reflect this interaction, but most studies have employed only a one-way or partial equilibrium adjustment process. We view our analysis as a first step toward improved analysis of linked market and land-use responses to forest policies involving carbon offsets, which we hope will stimulate future work in this area.

The base case (CO_2 price equals $0) simulation projects forest land losses to developed uses in western Oregon from 2010 to 2060 totaling about 409,000 acres from a starting base of nearly 6.5 million acres—a decline of about 6.3%. This decline is faster than previous projections using similar methods, which found a loss of 185,760 acres between 1994 and 2054—or about 2.6% (Kline, 2003). The inclusion of the 1994–2005 data in the land-use analysis partially explains this more rapid rate of forest loss. During the 1994–2005 period, a period of population growth in Oregon, structure counts increased by about 3.5% on forest land—compared to 1.7% from 1984 to 1994, the latest period used in earlier studies (Lettman et al., 2009: 24). Forecasts by Wear (2011: 39–41) for Oregon, California, and Washington combined using a coarser-scaled land-use classification model show forest land losses of 4.2 to 6.9% between 2010 and 2060, bracketing our own projection.

Overall, our simulation results emphasize the challenges and complexities of characterizing landowner responses to voluntary CO_2 sequestration policies. In the form examined here, CO_2 sequestration policies impact average forest land prices in western Oregon and have some potential to reduce forest land conversion to developed uses. This prospect is directly related to the carbon price, as would be expected, with prices in the range of $10 to $25 per tonne CO_2 reducing the loss of forest land by 100,000 to 160,000 acres (25% to 39%) over the 2010–2060 period relative to the base case. Forest land enrollment in the offset sales program in western Oregon would appear to be moderately responsive to carbon price in our simulations. A 1% increase in price in the $1 to $5 per tonne CO_2 range yields more than a 1% increase in enrollment. At prices between $5 and $50 per tonne CO_2, however, the price elasticity of enrollment declines sharply to the 0.44 to 0.23 range. This response occurs despite the fairly restrictive characteristics of the carbon offset program simulated, including a 100 year enrollment period and strict requirements to compensate for carbon lost through harvesting in both existing and regenerated stands.

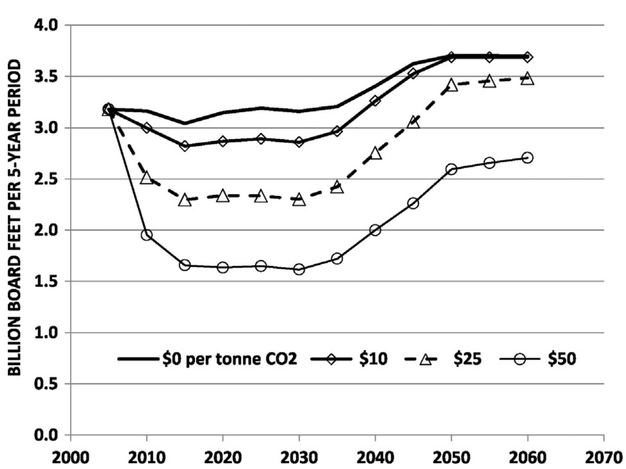

Fig. 5. Private softwood timber harvest in western Oregon by CO_2 price scenario.

In our simulations, silvicultural methods become simpler (rather than intensify) under a carbon offset program, particularly through the elimination of actions such as thinning and uneven-aged management that generate near-term carbon stock reductions and associated payments. In stands that are cut and regenerated during the simulation, those enrolled in the program are much more likely to employ planting (as opposed to natural regeneration) than areas not enrolled. Even at the lowest carbon prices it is optimal in some stands to never harvest areas enrolled (15% of enrolled area is uncut at $5 per tonne CO_2, 60% at $50). Timber harvest activity is shifted onto non-enrolled areas or deferred for some periods to the enrolled acres that are eventually cut. Non-enrolled areas make greater use of natural regeneration and employ thinning more extensively than the base case.

CO_2 prices of around $10 per tonne are approaching recent auction settlement prices of the California cap-and-trade (California Air Resources Board, 2015) and could be sufficient to keep regional private forest CO_2 stocks at or above current levels over the period to 2060. Higher carbon prices could lead to significant growth in stocks with the largest gains in the near-term (first 20 years). More immediate increments may be preferred to distant future increases, if climate change impacts behave according to a threshold process in atmospheric GHG concentrations as some climate scientists have suggested. We acknowledge that recent studies of forest carbon offset sales programs have commonly considered CO_2 prices well above the $50 upper level employed in this study (for example, one study looks at prices of $250 per tonne). Based on our simulation findings, however, prices at these levels would effectively preclude harvesting for timber products in western Oregon.

While interpreting our results, it should be born in mind that our model and inventory data base do not allow differentiation of private ownerships on the basis of size of ownership (parcel size) and any associated variation in the costs of participation in an offset sales program. Some recent surveys have suggested that smaller parcels may incur higher costs, thus serving as a disincentive to participate (see Håbesland et al., 2015, for an overview of these studies). Our costs assume an "average" size parcel based on the work by Galik et al. (2012). To the extent that we misrepresent the costs of different parcel size owners, our results may overstate enrollment of smaller owners and understate enrollment of larger sizes. We reiterate, however, that our study is (to our knowledge) unique in explicitly including any participation costs in the projections.

Another simplification in our analysis is the use of a set of fixed prices for carbon, implying that an unlimited amount of offsets in widely different parcel sizes could be sold with no price variation or limitations. This is certainly not the condition of current offset markets, but how demand may emerge as interest in offsets expands is unclear. Our primary interest in the present study is on supply-side behavior, however, so we have employed a highly simplified representation of demand response.

Finally, we believe that linked land-use and market model approaches such as the one demonstrated here could be used to improve understanding of the impacts of an array of forest policies beyond carbon offsets. Any policy that might affect forest land values, including tax laws, forest practice regulations and biodiversity restrictions, can involve both product market and land-use adjustments which influence their overall effects. Additionally, we recognize the potential significance of interactive effects between market and land-use adjustments in forestry and agriculture sectors. We assumed that agricultural returns remained constant for the duration of our simulations, because of the low likelihood of agricultural to forest land conversions in our western Oregon study area. In other regions, interactive effects between these two sectors could also influence carbon offset enrollment. Further investigating all of these possible interactions would provide useful avenues for future research.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.forpol.2016.01.004.

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