Supporting Information Text for *Efficiency of incentives to jointly increase carbon sequestration and species conservation on a landscape*

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The Parcel Map

The Willamette Basin of Oregon, U.S., was divided into 10,372 distinct parcels. The parcel map is defined in Polasky et al., forthcoming. It was formed by dividing a 1990 raster grid land-cover map (*1*) into parcels according to contiguous clumps of similar land-cover. Parcels formed thusly and that were significantly larger than 750 hectares were divided such that each newly formed parcel was approximately 750 hectares or less. The smallest parcel on the map is 0.09 hectares. For this study we ignore the 2,196 parcels that have any part of their area on or within Urban Growth Boundaries (UGBs) or are completely covered by water (this former simplification resulted in larger areas being covered by UGBs on our parcel map than the Willamette Basin actually has). Thus, the land use change, carbon sequestration, and species conservation models operate over 8,176 parcels.

Data on many parcel-level variables were collected. Some of the variables are described below. See Polasky et al., forthcoming for details on all parcel-level variables collected.

A land-use pattern is formed when each of the modeled 8,176 parcels is assigned a land-use category. Let the land-use of parcel *j* be given by X_j^i where $X_j^i = 1$ if parcel *j* is in land-use category *i* and equals 0 otherwise. Therefore, a land-use pattern is defined as,

$$\mathbf{X} = \left\{X_1^1,\ldots,X_1^I,\ldots,X_j^1,\ldots,X_j^I,\ldots,X_J^1,\ldots,X_J^I,\right\}$$
$$\sum\nolimits_{i=1}^{I} X_j^i = 1 \qquad \forall j \tag{1}$$
$$X_j^i = \{0,1\} \qquad \forall i, j$$

Our model includes 14 land-use categories: Orchard/Vineyard (i = 1); Grass Seed (i = 2); Pasture (i = 3); Row Crops (i = 4); Managed Forestry (i = 5); Rural-Residential Housing (i = 6); Oak Savanna (i = 7); Prairie (i = 8); Old Growth Conifer (i = 9); Mixed Forest (i = 10); Oak and Other Hardwood (i = 11); Riparian Forest (i = 12); Emergent Marsh (i = 13); and Scrub/Shrub (i = 14).

The initial land-use pattern on the parcel map was defined using the same 1990 raster grid land-cover map that was used to define parcels. See (*2*) for details on the creation of this initial land-use pattern. However, two decisions made when making the initial land-use pattern deserve mention here. First, if the initial land-use on a parcel was *agriculture*, the agricultural land-use category (i = 1, 2, 3, or 4) with the greatest expected net revenue was assigned to the parcel (the 1990 raster grid map does not distinguish among agricultural land-use categories). See (*2*) for detailed information on the model used to predict net revenue for each crop category on each parcel. In addition, the assignment rules stipulated that if any part of the parcel was in rural-residential use in the 1990 raster grid land-cover map than the rural-residential category (i = 6) was assigned to the whole parcel. This simplification resulted in larger areas covered by the rural-residential category on the initial land-use pattern map than the Willamette Basin had in 1990.

The land tenure status on each parcel was determined by overlaying a 2005 land ownership and land stewardship map (*3*) on the parcel map. On the ownership and stewardship map each polygon has been assigned a conservation status code of 1 through 4 as defined by the USGS Gap Analysis Program (*4*). A Gap code of 1 denotes complete conservation land-use (e.g., national parks and wilderness areas). A Gap code of 2 has been assigned to lands with limited commodity production or use activities (e.g., state parks, US Fish and Wildlife Refuges, and city or county parks). Polygons that have been assigned a Gap code of 3 are conserved land use over the majority of their area, but are used for extractive activities such as logging or mining (e.g., most US Forest Service lands). Finally, land used primarily for commodity production has been assigned a Gap code of 4. In this research we do not consider policies that could affect land use on parcels that have been assigned Gap codes of 1 through 3 or are in Indian

Tribal and Trust Land public land. Therefore, land use on these parcels remains static. All parcels that have been assigned a Gap code of 4 were considered to be privately owned and except for the rare cases, not managed for conservation on the initial land-use pattern. The policies used in this research are designed to affect land-use choice on these private parcels.

Econometric Model of Land-Use Change

A national-level econometric land-use model is used to project land-use changes on all privately owned parcels in the Willamette Basin. Specifically, the model estimates a land-use transition matrix to characterize exchanges among six land-use categories. Each element of the matrix gives the probability that a landowner will transition from her initial land use (given by the initial land-use pattern map) to another as a function of economic decision variables and parcel-level characteristics.

The econometric model is described in detail in (*5*). The model makes several simplifying assumptions. First, landowners are assumed to choose the land use that maximizes the present discounted value of the stream of expected net revenues from the land. Furthermore, it assumes that landowners base their expectations of future net revenues on current and historic values of relevant variables. Net revenues are defined as the quantity of the good produced from land multiplied by its price less the opportunity cost of all variable inputs to production. Given these assumptions, a simple decision rule emerges from the related dynamic optimization problem (*6*). In time t, the landowner chooses the use with the highest expected one-period net revenues at time t minus the current one-period expected opportunity cost of undertaking conversion. Formally, the owner of a parcel in use i will transition from land-use i to k at time t if:

$$R_{kt} - C_{ikt} \geq R_{lt} - C_{ilt} \qquad (2)$$

for all uses $l \neq k$, where R_{kt} and R_{lt} represent the expected net revenues at time t from a parcel of land in uses k and l, respectively, and C_{ilt} is the expected annualized cost of converting from use i to use l at time t (C_{iit} =0). If the current use i satisfies equation (2), then the parcel remains in that use at time t; otherwise, the landowner will reallocate the land to the use $k \neq i$ that maximizes expected net revenues minus conversion costs.

In practice, private land-use decisions can be influenced by factors other than market returns. For example, landowners may derive non-market benefits from their land (e.g., from recreation or aesthetics) or have historical ties to the land in particular uses (e.g., family-owned farms). Data are available to measure the net revenue variables (or construct suitable proxies) in equation (2); however, these additional factors are unobservable. As such, we model them as random disturbances and modify equation (2) as follows:

$$R_{kt} - C_{ikt} + \varepsilon_{kt} \geq R_{lt} - C_{ilt} + \varepsilon_{lt} \qquad (3)$$

where ε_{kt} and ε_{lt} are random variables associated with uses k and l, respectively. Because of the unobserved components, we can now make only probabilistic statements about land-use decisions. By imposing distributional assumptions on the random variables (*7*), we obtain a parametric expression for the probability that a parcel in use i will be allocated to use k conditional on the net revenue and cost variables. The goal of the econometric modeling is to estimate the parameters of the land-use transition probabilities. The estimation yields response functions indicating the probability of land-use changes conditional on economic variables.

The National Resources Inventory (NRI) is the primary data set used to estimate a national land-use model. The NRI is a panel survey of land use and land characteristics on non-federal lands conducted at 5-year intervals from 1982 to 1997 over the entire United States, excluding Alaska. Data include approximately 844,000 plot-level observations, each representing a land area given by a sampling weight. The NRI provides information on land-use transitions over the periods 1982-87, 1987-92, and 1992-97. The econometric analysis focuses on the contiguous U.S. and six major land uses: crops, pasture, forest, urban, range, and land enrolled in the federal Conservation Reserve Program. This land base comprises 1.4 billion acres, representing about 74% of the total land area and 91% of non-federal land in the contiguous U.S.

Distributional assumptions imposed on the random terms in equation (3) yield a nested logit model for estimation (*7*). The dependent variable is the land-use choice in year t+5 (t = 1982, 1987, 1992) at each NRI plot. The land-use transition probabilities are given by:

$$P_{jikt} = f\left(\boldsymbol{\beta}_{ik}, \mathbf{NR}_{jt}, \mathbf{LQ}_{j}\right) \quad (4)$$

for all j, i, k, and t, where j indexes the plot, $\boldsymbol{\beta}_{ik}$ is a vector of parameters associated with the transition from use i to k, $\mathbf{NR}_{jt}$ is a vector of net revenue variables for plot j in time t, and $\mathbf{LQ}_j$ is a vector of plot-level variables measuring land quality. By assembling data from a variety of private and public sources, (*8*) constructed county-level estimates of annual per-acre net revenues for crops, pasture, forest, range, and urban uses for all 3,014 counties in the conterminous U.S. Conversion costs are measured implicitly with constant terms specific to each transition. The land-quality measure is an indicator variable for the land capability class rating of NRI plots (*9*). These variables reflect the productivity of the land and are interacted with the net revenue and conversion cost variables to allow for plot-level deviations from the county average net revenue.

Details on the estimation procedure and results are provided in (*8*) and (*5*). The parameter estimates ($\boldsymbol{\beta}_{ik}$) are substituted into equation (4) to yield response functions indicating the probabilities of land-use transitions among potential land uses for given values of the net revenue and land-quality variables. Because of this dependence on the economic and plot-level variables, a set of response functions is defined for each plot j and time t.

Using equation (4), national-level estimated parameter values, and spatial landscape data from the Willamette Basin, land-use transition probabilities are computed for each privately owned parcel in the Willamette Basin (see (*10*) for more details on this procedure). Probabilities are calibrated so that they correspond to the study's 50-year time period (approximately 1990 to 2040). Using a random number generator, we simulate land-use change decisions on each parcel in the Basin (see (*10*) for details). If a parcel is not projected to change land use, it remains in its initial land-use. Repeated simulations are done to construct 500 base land-use patterns. In each case, it is assumed that publicly-owned land does not change use. This framework can also be used to represent the landowner's choice to contract for conservation, as discussed in the next section.

Policy Simulation

In order to simulate the effect of a conservation policy on land-use change in the Willamette Basin, we need to determine how much a private landowner would need to be paid to be indifferent between maintaining her predicted baseline land use and converting to her parcel-specific conservation land use. This indifference point is a landowner's willingness-to-accept (WTA) level for a conservation contract.

The econometric model yields transition probabilities associated with the broad land uses of cropland, pasture, forest, and urban land. Given these definitions, the finer GIS classification for conserved land uses (e.g., prairie, oak savanna, old growth conifer, etc.) must be associated with one of the broader classifications from the econometric model. We link the two classifications by exploiting the assumption that the transition probabilities implictly account for unobservable non-market attributes associated with land (e.g., pheasant hunting on cropland). This assumption is implicit given the econometric specification of stochastic error terms. Each conservaiton land use is assumed to provide similar non-market attributes to an income-generating land-use. In particular, all conifer land uses with trees (e.g., old-growth conifer) are assumed to provide similar non-market attributes as an income-generating parcel that is in forestry. Conservaiton land uses of prairie, oak savanna, scrub/shrub, or emergent marsh are assumed to provide similar non-market attributes as an income-generating parcel that is in cropland. The relevant simulation estimates the distribution of each landowner's WTA for placing commercial cropland into "conserved" cropland (CC), commercial cropland into "conserved" forestland (CF), and commercial forestland into "conserved" forestland.

We calculate the distribution of WTA by exploiting the functional relationship between the transition probabilities and the net returns to alternative land uses. In particular, suppose parcel j begins in land-use i and has a potential conservation land-use n. Absent any conservation payment, the econometric model generates baseline transition probabilities $P_{jikt} = f\left(\boldsymbol{\beta}_{ik}, \mathbf{NR}_{jt}^{B}, \mathbf{LQ}_{j}\right)$ between use i and all possible land-uses k, including use n, where $\mathbf{NR}_{jt}^{B}$ refers to the vector of baseline land-use net returns. Net retuerns are in per acre terms. We simulate a conservation payment by altering the net-returns to use n in increments of S_g dollars. For the CC and CF transitions, the following is used:

$$\Pr\left(WTA_{in} \le S_g\right) = P_{jiit}\left(\boldsymbol{\beta}_{ik}, \mathbf{NR}_{jt}^{B}, \mathbf{LQ}_{j}\right) - P_{jiit}\left(\boldsymbol{\beta}_{ik}, \mathbf{NR}_{jt}^{B} - S_g, \mathbf{LQ}_{j}\right) \quad (5)$$

where $\boldsymbol{S_g}$ is a vector of payments that are non-zero only for use n. We assume that the net-returns to use n are altered with the following increments: S_0 = \$0, S_1 = \$10, ….., S_{10} = \$100, S_{11} = \$125,….., S_{22} = \$400 per acre, such that we generate N = 22 distinct WTA probabilities. Since the conserved land uses are not separately defined use within the econometric model, changes within cropland and forestland requires a reduction in the net returns to these uses, where the probability of remaining in income-producing use i is $P_{jiit}\left(\boldsymbol{\beta}_{ik}, \mathbf{NR}_{jt}^{B} - S_g, \mathbf{LQ}_{j}\right)$, and the probability of converting to the other non-conservation land uses remains at the baseline to assure that the probabilities sum to one: $P_{jikt} = f\left(\boldsymbol{\beta}_{ik}, \mathbf{NR}_{jt}^{B}, \mathbf{LQ}_{j}\right) \quad \forall k \ne i, n$. The WTA probability for converting cropland to "conserved" forestland (CF) is defined as:

$$\Pr\left(WTA_{in} \le S_g\right) = P_{jikt}\left(\boldsymbol{\beta}_{ik}, \mathbf{NR}_{jt}^{B} + S_g, \mathbf{LQ}_{j}\right) - P_{jikt}\left(\boldsymbol{\beta}_{ik}, \mathbf{NR}_{jt}^{B}, \mathbf{LQ}_{j}\right) \quad (6)$$

where the probability of converting between i and non-conservation land-use k is $P_{jikt} = f\left(\boldsymbol{\beta}_{ik}, \mathbf{NR}_{jt}^{B} + S_g, \mathbf{LQ}_{j}\right) \quad \forall k \ne n$ to assure that the probabilities sum to 1. Regardless of whether the initial land use is the conserved land use, the probability of converting a parcel of land to the conseved land use monotonically increases as the conservation payments are increased.

We use a random number generator to estimate a distribution of WTA per acre values for each private parcel on the landscape. The process works as follows:

1. A random number r is generated from a uniform distribution defined on the unit interval and compared to each of the estimated WTA probabilities.
2. If $Prob\left(WTA \le S_g\right) < r \le Prob\left(WTA \le S_{g+1}\right)$, then WTA is assumed to equal $(S_g + S_{g+1})/2$. If $r > Prob(WTA \le \$400)$, the landowner is assumed to have an infinite WTA.
3. Return to step 1.

This process is repeated for each of the 500 baseline land-use patterns that were generated earlier. Thus we generate 500 WTA vectors where one corresponds to each baseline land-use pattern.

We exploit the first-order Markov properties of the 5-year transition probabilities to calculate transition probabilities over a 50-year horizon. For example, for a parcel starting in cropland in year 0 (i.e., 1990) and ending in forest in year 50 (i.e., 2040), the probabilities for each possible way of reaching forest over this horizon are summed. Of course, this brings up the unlikely possibility that a parcel could change uses several times during the course of 50 years. However, since the probability of conversion in any one period is generally small, the probability of a parcel changing uses multiple times also tends to be small. In a similar analysis for South Carolina, (*11*) found that the probability that an agricultural parcel will transition to forest over a thirty-year time horizon in *only one transition* rather than multiple transitions is 99.3%. If a parcel is placed in conservation at any point over the 50-year horizon, it is assumed to remain in this conserved use for the remainder of the horizon.

Not all private parcels are asigned WTA values. We calculate WTA per acre values for all private parcels outside of Urban Growth Boundaries, that have a Gap code of 4, and that:

- begin in crops and have a conserved land use of prairie, oak savanna, scrub/shrub, or emergent marsh;
- begin in crops and have a forested conservation land use, or
- begin in forest and have a forested conservation land use.

These limitations mean that the following private parcels are not assigned WTA values:

- 255 parcels initially in pasture use (covering 25,849 hectares; as discussed in (*5*), the own-return elasticities for pasture are negative, though not significantly different from zero, which produces counter-intuitive results when used in the simulation);
- 653 parcels initially in rural-residential use (covering 101,998 hectares);
- 112 parcels initially in forested land use and a Pre-Euroamerican settlement land use (*12*) of prairie (covering 13,063 hectares); and
- 24 parcels initially in conserved land use with a Gap code of 4 (covering 1,734 hectares; these parcels may include Nature Conservancy or Conservation Reserve Program-enrolled land).

These eliminations leave 3,889 private parcels covering 1,315,685 hectares eligible for the broadest policy scenario, the *All* scenario. See SI Table 1 for a summary of the truncated WTA per acre values across all private parcels eligible for the *All* policy scenario. See SI Fig. 4 for a map of the truncated WTA per acre values across the private parcels eligible for a conservation contract under the *All* policy scenario.

The parcels eligible under each of the other scenarios are subsets of the parcels eligible under the *All* scenario. In the *Rare Habitat* policy scenario contracts are available to parcels that meet the *All* policy requirements and had a Pre-Euroamerican vegetation cover (*12*) of oak savanna ($i = 7$), prairie ($i = 8$), or emergent marsh ($i = 13$; these habitat types are currently the rarest in the Basin). There are 613 such parcels covering 184,159 hectares. In the *Carbon* policy scenario contracts are available to parcels that meet the *All* policy requirements and where conversion to Pre-Euroamerican vegetation cover (*12*) leads to afforestation vis-à-vis the initial land-use or conversion to old conifer forest ($i = 9$). There are 2,211 such parcels covering 788,407 hectares. In the *Riparian* policy scenario incentives are available to parcels that meet the *All* policy requirements and have a stream density of 10 or greater, where stream density is equal to the parcel's total stream length in meters per parcel area in meters squared. There are 1,941 parcels with a stream density of 10 or greater covering 740,162 hectares. In the *Species Conservation* policy scenario incentives are available to parcels that meet the *All* policy requirements and are identified as important species conservation sites in (*2*). There are 226 such parcels covering 86,068 hectares. SI Fig. 1 indicates the parcels that meet the requirements of each of the policy scenarios.

We assume that each private parcel converts to a conservation land use if offered a per acre conservation payment equal to or greater than the parcel's WTA per acre for conservation. Private parcels that convert to conservation land-use are assumed to eventually have a land cover corresponding to its Pre-Euroamerican settlement vegetation type (*12*).

To determine the annual per-acre conservation payment under a particular policy scenario we employ the following methodology:

1. First, we determine what parcels are eligible for a payment under the particular policy scenario.
2. Next, for each WTA vector we determine how many eligible parcels on the landscape would accept a contract if the per acre conservation contract price was \$Y.
3. Next, we determine the total amount of money that the regulator would pay out annually to a contracting parcel by multiplying the parcel's area in acres by the contract price of \$Y.
4. Next, we determine the amount of money that the regulator would pay out across the whole landscape.
5. Next we find the average landscape pay out across all 500 WTA vectors.
6. Finally, we vary the levels of \$Y until we find \$Y levels that generate average annual landscape-wide payouts that are close to the annual budgets of \$1 million, \$5 million and \$10 million.

See SI Table 2 for the annual per-acre conservation contract prices used for each policy scenario-conservation program budget level combination.

Simple Carbon Sequestration Model

The simple carbon sequestration model uses Intergovernmental Panel on Climate Change (IPCC; *13*) default carbon storage values for the 14 different land use categories (i = 1,…,14) found within the Willamette Basin to predict the carbon sequestered on each parcel as it segues from its initial to terminal land use. Carbon storage values in (*13*) are a function of land use and land-use age and the study area's climate- and eco-region. The Willamette Basin's climate region is *cool temperate moist* and its eco-region is *temperate oceanic forest*. The IPCC data was supplemented with other sources for the emergent marsh land use category (i = 13). Sources (*14*) and (*15*) were used to determine annual carbon sequestration rates in marsh soils and source (*16*) was used to determine the methane emitted from marshes to the atmosphere. The carbon sequestration time horizon used in this model is 50 years.

The carbon sequestered on parcel j over the 50-year time horizon is equal to the stock on j in terminal year T = 50 less the stock on j in year t = 1. Specifically, let the amount sequestered on j over 50 years that begins in land-use i of age a and terminates in land use k be given by $C_{ji_a k}$:

$$C_{ji_a k} = \left(\sum_{k_b=1}^{3} \alpha_{i_a k_b T} C_{k_b}\right) + \beta_{ikT} HWP_k + \gamma_{ikT} CCHWP_{i_a} - \delta_{ikT} HWP_i - C_{i_a} \tag{7}$$

The variables in equation (7) include:

- C_{k_b} is the carbon stored (metric tons per hectare) on land-use k of age class b ($b \in$ { young = 1 , moderate = 2, old = 3}) at the terminal time period T = 50. This includes carbon in the following 5 carbon pools: soil, belowground biomass, aboveground biomass, deadwood, and ground litter.
- $\alpha_{i_a k_b T}$ adjusts the terminal carbon stock in parcel j as a function of i_a, k_b, and T. In this case, $\alpha_{i_a k_b T} \in \{0,1\}$ and $\sum_{k_b=1}^{3} \alpha_{i_a k_b T} = 1$ for most i_a and k_b combinations (the few exceptions are explained below).
- HWP_k is the total amount of carbon stored (metric tons per hectare) in harvested wood product produced by land-use k in equilibrium.
- β_{ikT} indicates that fraction of equilibrium HWP_k that has been generated by k or remains from land-use i 50 years after a change from i to k.
- $CCHWP_{i_a}$ is the total amount of carbon stored (metric tons per hectare) in the wood-products removed 50 years ago due to a clear-cut of land-use i of age a.
- γ_{ikT} indicates whether or not the transition from i to k resulted in a clear-cut of i's wood.
- HWP_i is the total amount of carbon stored (metric tons per hectare) in HWP produced by land use i in equilibrium.
- δ_{ikT} indicates whether land-use i generates harvest wood products .
- C_{i_a} is the carbon stored (metric tons per hectare) on land-use i of age class a ($a \in$ {young = 1 , moderate = 2, old = 3}) at the initial time period t = 1.

In this model we assume that if a parcel transitions from use i to k ($i \neq k$), then transition happens immediately on the landscape. (i.e., the transition occurs in the first year of a 50-year modeling timeframe).

Source (*13*) gives a range of values for C_{i_a}, C_{k_b}, HWP_i, HWP_k, and $CCHWP_{i_a}$. The low and high bounds for these variables are given in SI Tables 3-4.

As noted above, $\alpha_{i_a k_b T}$ equals 0 or 1 except for a few cases. One exception is prairie land use that transitions to old growth conifer land use. Fifty years after a transition from prairie to a conifer forest (recall that T = 50) the parcel will not be in old conifer's lowest age class yet (old conifer's lowest age class is 120 to 140 years old). Therefore, in this case,

$$\left(\sum_{k_b=1}^{3} \alpha_{i_a k_b T} C_{k_b}\right) = 0.6C_{OldGrowth_1} + 0.0C_{OldGrowth_2} + 0.0C_{OldGrowth_3} = 0.6\,C_{jkb} \quad (8)$$

where i_a = prairie and k_b = old growth conifer, young age class. In this case we assume that after 50 years a parcel transitioning from prairie to old conifer will have accumulated 60% of the old conifer, young age class carbon storage value. The other cases where $\alpha_{i_a k_b T}$ does not equal 0 or 1 are listed in SI Table 5.

For simplification, equation (6) also assumes that a parcel that initially starts in a non-forested land-use (i = 1-4, 6-8) and transitions to managed forestry (i = 5) will not generate any *HWP* over the 50-year time horizon given a typical Basin managed forestry rotation time of 45 years. Finally, equation (6) assumes that a parcel that begins in a non-managed forested land use and transitions to managed forestry will be managed such that the managed forest has reached its production equilibrium by the 50th year of the model. The exception to this is the non-managed forested land-use types of oak and other hardwood (i = 11) and riparian forest (i = 12), which, due to lower production capacities, are assumed to be only half-way to their equilibrium production 50 years after transitioning to a managed forestry land use (note that oak savanna is not considered a forested land use). All of these assumptions are reflected in the values of $\alpha_{i_a k_b T}$, β_{ikT}, and δ_{ikT}. See SI Tables 6-8 for the values of β_{ikT}, γ_{ikT}, and δ_{ikT}.

1. Model Simulation

We randomly assign a C_{i_a} value to j 1000 times given j's initial land-use category i and a randomly assigned age class a. The carbon sequestration value, C_{ji_ak}, is then calculated on each j for every land-use transition possibility on the landscape (i.e., i_a to k = 1, 2,…,14) 1,000 times. Therefore, we create one-thousand 8176 x 14 matrices of carbon sequestration values where rows index j and the columns index all the land-use transition possibilities on the landscape, including j remaining in its initial land-use across the 50-year modeling period. We then generate an average C_{ji_ak}, given by $\overline{C}_{jk}$, for each j and land-use transition possibility on the landscape by averaging across each relevant element in the 1000 matrices.

The 8176 x 14 matrix of $\overline{C}_{jk}$ values is used to look up the average per hectare carbon sequestration value for each parcel on a baseline and policy-generated land-use pattern. Next, each parcel's per hectare carbon sequestration value is multiplied by a parcel's area in hectares to calculate the parcel's carbon sequestration performance over 50 years. A landscape-wide carbon sequestration value for the land-use pattern being analyzed is then calculated by summing across all parcels' sequestration values. The simple landscape-wide results are normalized by dividing the calculated value by the maximum carbon sequestration potential on the landscape (i.e., each parcel j transitions to land-use category k that maximizes C_{ji_ak}).

The 8176 x 14 look-up table of $\overline{C}_{jk}$ values is also used when determining the simple model efficiency frontiers. In the optimization routine used to determine the simple model efficiency frontiers, described in equations (75)-(81), $\overline{C}_{jk}$ is represented by $\overline{G}_j^i$ where i, in this case, is equivalent to k.

Complex Carbon Sequestration Model

First, the following was calculated for each parcel j:

- a binary variable indicating whether parcel j has low (*soil* = 0) or high (*soil* = 1) quality soil;
- a binary variable indicating whether parcel j has a low (*si* = 0) or high (*si* = 1) Douglas fir site index value; and
- a binary variable indicating whether parcel j is in a riparian zone (*riparian* = 1) or not (*riparian* = 0).

A parcel has high quality soil (*soil* = 1) if 50% or more of the parcel's soil profile is in USDA soil categories I thorough III, either for irrigated or non-irrigated soil (*17*). Otherwise a parcel's soil is of low quality (*soil* = 0). A parcel has a high Douglas Fir forest site index (*si* = 1) if its 50-year Douglas Fir site index is greater than 95 (*17*). Otherwise, the parcel is assigned a low Douglas fir forest site index (*si* = 0). Further, a parcel with a stream length to area ratio of 10 to 1 (meters to square meters) or greater has a riparian zone indicator of 1 (*18*). Otherwise the parcel has a riparian zone indicator of 0.

In addition, the following values were calculated for a subset of parcels:

- the fraction of softwood on a parcel when it was clear-cut (*OSoftW*);
- the fraction of softwood on a parcel when it was clear-cut (*OHardW*); and
- the extent of canopy cover on the parcel when it was clear-cut (OCC_j)

OSoftW, *OHardW*, and *OCC* values are only assigned to *j* if it has,

- a forested type cover on the Pre-Euroamerican settlement vegetation map (*12*); and
- a commodity land use (*i* = 1-6) on the initial land-use pattern.

OSoftW, *OHardW*, and *OCC* are random variables with a uniform distribution.

As noted above, each parcel on the landscape was assigned an initial land-use category indexed by *i* = 1,…,14. Based on its initial land-use category, other information found on the 1990 raster grid land-cover map and other parcel-related data, including *soil*, *si*, and *riparian* values, each parcel was assigned an initial sub-land-use category indexed by *d* = 1,…,43. See SI Tables 9-10 for a list of the sub-categories and details on how *j* was assigned a sub-land-use category *d*.

For each *d* the following tree stand information was determined:

- low and high bounds on fraction of *d*'s tree stands that are in Douglas Fir (*SoftW*);
- low and high bounds on the average age of *d*'s stands of Douglas Fir (*SoftAge*);
- low and high bounds on the average age of *d*'s stands of Alder / Maple (*HardAge*); and
- low and high bounds on *d*'s extent of canopy coverage (*CC*).

Tree stand data as a function of *d* is based on information from (*19*). For covers with a canopy coverage fraction greater than 0 (*CC* > 0) the fraction of *d*'s stands in Alder / Maple (*HardW*) is equal to 1–*SoftW*. The low and high bounds for all tree stand variables for each *d* are given in Table SI 11.

For each *d* the following miscellaneous information was also determined: 1) low and high bounds on carbon sequestered (metric tons per hectare) in non-tree root mass at sequestration equilibrium (*RootMass*); and 2) low and high bounds on the number of years it takes to reach carbon sequestration equilibrium in non-tree root mass after a change to sub-land cover category *d* (*RootEqu*). Carbon in non-tree root mass at equilibrium as a function of *d* is based on information in (*20*) and (*21*). See Table SI Table 12.

Carbon sequestration rates in soils were also determined for each *d*. For sub-land-uses $d \in [1,8]$, $d \in [11,28]$ and $d \in [39,43]$ low and high bounds on carbon stored (metric tons per hectare) in soil at sequestration equilibrium (*SoilMass*) and low and high bounds on the number of years it takes to reach storage equilibrium in soil after a change to sub-land cover category *d* (*SoilEqu*) were determined using (*22*), (*23*), (*24*), (*25*), (*26*), (*27*), (*21*), (*28*), (*29*), (*5*), (*30*), and (*31*). See SI Table 13. For all other sub-land-use categories carbon storage in soil is based on functions from (*31*). For these other sub-land use categories carbon stored in soil is a function of forest stand age. Finally, low and high bounds on carbon stored (metric tons per hectare) in a stand of orchard plants at equilibrium (*OrchardBiomass*) was taken from Kroodsma and Field (32). In this model $OrchardBiomass_j$ ranges from 0 to 48 metric tons per hectare.

In order to run this model each parcel *j* must be assigned an initial value for each of the following variables as a function of its sub-land-use *d* category:

- $SoftAge_j$
- $HardAge_j$
- CC_j
- $RootMass_j$

- $RootEqu_j$
- $OrchardBiomass_j$

Further, for each j a managed forestry operation age is assigned. Let this variable be represented by Age_j and have bounds of 46 and 91 years. Finally, if j's $d \in [1,8]$, $d \in [11,28]$ or $d \in [39,43]$ then j is assigned an initial value for the variables $SoilMass_j$ and $SoilEqu_j$ as a function of its d category. For other sub-land-use categories d, $SoilMass_j$ and $SoilEqu_j$ are determined by an equation that is a function of $SoftAge_j$ and $HardAge_j$ (see below).

1. Carbon sequestered in a parcel over time

The complex carbon sequestration model tracks carbon sequestration in each pool on each parcel over 50 years. The pools include wood (*Wood*), standing dead wood (*DWood*), wood understory (*Under*), down dead wood (*DDWood*), other forest floor debris (*FFloor*), soil (*Sl*), non-tree root mass (*Rt*), any other biomass (*OthBiomass*), and any carbon remaining in harvested wood product that was removed from the parcel in the past (*HWP*). Let t index time where $t = 1$ is the initial time period. The annual gain or loss in carbon in each carbon pool on each j is discounted at a 5% rate and the total discounted change in each pool in each j over the 50-year time period is given by the following series of equations,

$$\Delta Wood_j = \sum_{t=1}^{49} \left(Wood_{jt+1} - Wood_{jt}\right) / \left(1.05^t\right) \quad (9)$$

$$\Delta DWood_j = \sum_{t=1}^{49} \left(DWood_{jt+1} - DWood_{jt}\right) / \left(1.05^t\right) \quad (10)$$

$$\Delta Under_j = \sum_{t=1}^{49} \left(Under_{jt+1} - Under_{jt}\right) / \left(1.05^t\right) \quad (11)$$

$$\Delta DDWood_j = \sum_{t=1}^{49} \left(DDWood_{jt+1} - DDWood_{jt}\right) / \left(1.05^t\right) \quad (12)$$

$$\Delta FFloor_j = \sum_{t=1}^{49} \left(FFloor_{jt+1} - FFloor_{jt}\right) / \left(1.05^t\right) \quad (13)$$

$$\Delta Sl_j = \sum_{t=1}^{49} \left(Sl_{jt+1} - Sl_{jt}\right) / \left(1.05^t\right) \quad (14)$$

$$\Delta Rt_j = \sum_{t=1}^{49} \left(Rt_{jt+1} - Rt_{jt}\right) / \left(1.05^t\right) \quad (15)$$

$$\Delta OthBiomass_j = \sum_{t=1}^{49} \left(OthBiomass_{jt+1} - OthBiomass_{jt}\right) / \left(1.05^t\right) \quad (16)$$

$$\Delta HWP_j = \sum_{t=1}^{49} \frac{\left(MFHWP_{jt+1} - MFHWP_{jt}\right) + \left(CCHWP_{jt+1} - CCHWP_{jt}\right) + \left(CCSHWP_{jt+1} - CCSHWP_{jt}\right)}{\left(1.05^t\right)} \quad (17)$$

By summing across equations (9) through (17) the total sequestration on parcel j from time $t = 1$ to $t = 50$ is determined. The functions *MFHWP*, CCHWP, and *CCSHWP* are explained below.

Let us define two distinct periods of sequestration on each parcel j: before and after a land-use change from land-use category i to k where k indicates the terminal land-use and $t = z$ indicates the year of land-use change from i *to* k on j. Therefore, the first period of carbon sequestration occurs from $t = 1$ to $t = z$ and the second period occurs from $t = z$ to $t = 50$. If the land use on j does not change then $z = 50$ and j only experiences the first period of carbon sequestration.

As with the initial land-use pattern map, each land-use category k on j is associated with a sub-land-use category. We signify the post-transition sub-land-use category with the index d^*. The particular d^* assigned to j is a function of k and j's *soil*, *si*, and *riparian* values. See SI Table 12 for these transition limitations.

2. Annual carbon sequestration before a land-use transition

2a. Carbon sequestration before a land-use transition if $d \neq 9$ or 10

In this section annual sequestration in j during the time period $t \leq z$ given the d on j does not indicate managed forestry land-use ($d \neq 9$ or 10) is addressed. Under these conditions, the annual sequestration of carbon in metric tons per hectare in the pools *Wood, DWood, Under, DDWood, and FFloor* are given by the following series of equations:

$$\begin{aligned} Wood_{jt+1} - Wood_{jt} \mid t+1 \leq z = {} & \left(SWB\left(SoftAge_j + t, \theta_j, si_j, E_j\right) \times SoftW_j \times CC_j\right) + \\ & \left(HWB\left(HardAge_j + t, \theta_j, si_j\right) \times HardW_j \times CC_j\right) - \\ & \left(SWB\left(SoftAge_j + t - 1, \theta_j, si_j, E_j\right) \times SoftW_j \times CC_j\right) - \\ & \left(HWB\left(HardAge_j + t - 1, \theta_j, si_j\right) \times HardW_j \times CC_j\right) \end{aligned} \tag{18}$$

$$\begin{aligned} DWood_{jt+1} - DWood_{jt} \mid t+1 \leq z = {} & \left(SDW\left(SoftAge_j + t, \theta_j, si_j, E_j\right) \times SoftW_j \times CC_j\right) + \\ & \left(HDW\left(HardAge_j + t, \theta_j, si_j\right) \times HardW_j \times CC_j\right) - \\ & \left(SDW\left(SoftAge_j + t - 1, \theta_j, si_j, E_j\right) \times SoftW_j \times CC_j\right) - \\ & \left(HDW\left(HardAge_j + t - 1, \theta_j, si_j\right) \times HardW_j \times CC_j\right) \end{aligned} \tag{19}$$

$$\begin{aligned} Under_{jt+1} - Under_{jt} \mid t+1 \leq z = {} & \left(SUnder\left(SoftAge_j + t, \theta_j, si_j, E_j\right) \times SoftW_j \times CC_j\right) + \\ & \left(HUnder\left(HardAge_j + t, \theta_j, si_j\right) \times HardW_j \times CC_j\right) - \\ & \left(SUnder\left(SoftAge_j + t - 1, \theta_j, si_j, E_j\right) \times SoftW_j \times CC_j\right) - \\ & \left(HUnder\left(HardAge_j + t - 1, \theta_j, si_j\right) \times HardW_j \times CC_j\right) \end{aligned} \tag{20}$$

$$\begin{aligned} DDWood_{jt+1} - DDWood_{jt} \mid t+1 \leq z = {} & \left(SDDW\left(SoftAge_j + t, \theta_j, si_j, E_j\right) \times SoftW_j \times CC_j\right) + \\ & \left(HDDW\left(HardAge_j + t, \theta_j, si_j\right) \times HardW_j \times CC_j\right) - \\ & \left(SDDW\left(SoftAge_j + t - 1, \theta_j, si_j, E_j\right) \times SoftW_j \times CC_j\right) - \\ & \left(HDDW\left(HardAge_j + t - 1, \theta_j, si_j\right) \times HardW_j \times CC_j\right) \end{aligned} \tag{21}$$

$$\begin{aligned} FFloor_{jt+1} - FFloor_{jt} \mid t+1 \leq z = {} & \left(SFF\left(SoftAge_j + t, \theta_j, si_j, E_j\right) \times SoftW_j \times CC_j\right) + \\ & \left(HFF\left(HardAge_j + t, \theta_j, si_j\right) \times HardW_j \times CC_j\right) - \\ & \left(SFF\left(SoftAge_j + t - 1, \theta_j, si_j, E_j\right) \times SoftW_j \times CC_j\right) - \\ & \left(HFF\left(HardAge_j + t - 1, \theta_j, si_j\right) \times HardW_j \times CC_j\right) \end{aligned} \tag{22}$$

where:

- *SWB* and *HWB* are allometric equations that give the metric tons of carbon per hectare stored in the wood of a fully closed tree stand of soft wood (Douglas Fir or Douglas Fir-Spruce-Mountain Hemlock mix) and hard wood (Alder / Maple) in the Pacific Northwest, West region, respectively, as a function of j's tree stand age (*SoftAge* and *HardAge*), whether or not the current tree stand on j is a product of afforestation or reforestation (as indicated by θ), j's Douglas fir 50-year site index (*si*), and j's elevation in meters (*E*).
- *SDW* and *HDW* are allometric equations that give the metric tons of carbon per hectare stored in the standing dead wood of a fully closed tree stand of soft wood and hard wood in the Pacific Northwest, West region, respectively.
- *SUnder* and *HUnder* are allometric equations that give the metric tons of carbon per hectare stored in the tree understory of a fully closed tree stand of soft wood and hard wood in the Pacific Northwest, West region, respectively.

- *SDDW* and *HDDW* are allometric equations that give the metric tons of carbon per hectare stored in the downed dead wood of a fully closed tree stand of soft wood and hard wood in the Pacific Northwest, West region, respectively.
- *SFF* and *HFF* are allometric equations that give the metric tons of carbon per hectare stored in the other forest floor debris of a fully closed tree stand of soft wood and hard wood in the Pacific Northwest, West region, respectively.

All allometric functions are from (*31*). In this research we assume θ_j indicates reforestation for all *j*. If a parcel has an average elevation of 1,600 meters or greater the Douglas Fir-Spruce-Mountain Hemlock allometric functions are used to describe the carbon content of a softwood stand; otherwise the Douglas fir allometric functions are used. If *j*'s $si_j = 0$ all allometric equation values are reduced by 5% and if $si_j = 1$ all allometric equation values are increased by 5%.

If $d \in [1,8]$, $d \in [11,28]$, or $d \in [39,43]$ then Sl_{j1} is given by $SoilMass_j$ and $Sl_{jt+1} - Sl_{jt} \mid t+1 \le z = 0$ for all $t \le z$. See SI Table 13 for the distribution of $SoilMass_j$ as a function of *j*'s *d* value. Otherwise, if $d \in [29,38]$ *j*'s annual carbon change in its *Sl* pool is given by:

$$\begin{aligned} Sl_{jt+1} - Sl_{jt} \mid t+1 \le z = {} & \left(SSoil\left(SoftAge_j + t, soil_j, \theta_j, si_j, E_j\right) \times SoftW_j \times CC_j\right) + \\ & \left(HSoil\left(HardAge_j + t, soil_j, \theta_j, si_j\right) \times HardW_j \times CC_j\right) - \\ & \left(SSoil\left(SoftAge_j + t - 1, soil_j, \theta_j, si_j, E_j\right) \times SoftW_j \times CC_j\right) - \\ & \left(HSoil\left(HardAge_j + t - 1, soil_j, \theta_j, si_j\right) \times HardW_j \times CC_j\right) \end{aligned} \quad (23)$$

where *SSoil* and *HSoil* are allometric equations that give the metric tons of carbon per hectare stored in the soil of a tree stand of soft wood and hard wood in the Pacific Northwest, West region, respectively. If *j*'s $soil_j = 0$ all allometric equation values from equation (23) are reduced by 5% and if $soil_j = 1$ all allometric equation values in equation (23) are increased by 5%.

Rt_{j1} is is given by $RootMass_j$ and $Rt_{jt+1} - Rt_{jt} \mid t+1 \le z = 0$ for all $t \le z$. See SI Table 14 for the distribution of $RootMass_j$ as a function of *j*'s *d* value.

$OthBiomass_{j1}$ is given by *j*'s initially assigned $OrchardBiomass_j$ and $OtBiomass_{jt+1} - OthBiomass_{jt} \mid t+1 \le z = 0$ for all $t \le z$.

Finally, the annual change in the carbon stored in wood products generated by timber clear-cut from *j SoftAge+t* and *HardAge+t* years ago is given by,

$$\begin{aligned} CCHWP_{jt+1} - CCHWP_{jt} \mid t+1 \le z = {} & \left(SHWP\left(SoftAge_j + t, si_j\right) \times SWB\left(50, \theta_j, si_j, E_j\right) \times OSoftW_j \times OCC_j\right) + \\ & \left(HHWP\left(HardAge_j + t, si_j\right) \times HWB\left(50, \theta_j, si_j, E_j\right) \times OHardW_j \times OCC_j\right) - \\ & \left(SHWP\left(SoftAge_j + t - 1, si_j\right) \times SWB\left(50, \theta_j, si_j, E_j\right) \times OSoftW_j \times OCC_j\right) - \\ & \left(HHWP\left(HardAge_j + t - 1, si_j\right) \times HWB\left(50, \theta_j, si_j, E_j\right) \times OHardW_j \times OCC_j\right) \end{aligned} \quad (24)$$

where $SHWP_j$ and $HHWP_j$ are Pacific Northwest, West region allometric equations that give the fraction of carbon that remains in harvested wood removed *SoftAge+t* ot *HardAge+t* years ago as a function of *j*'s site index. As already mentioned, the parcel-specific variables in equation (24) are determined by the type of forest found on the parcel before Euroamerican settlement (*12*, *19*). Equation (24) assumes that the wood stands clear-cut $SoftAge_j + t$ and $HardAge_j + t$ years ago were 50 years old. As before, if $si_j = 0$ all allometric equation values in equation (24) are reduced by 5% and if $si_j = 1$ all allometric equation values in equation (24) are increased by 5%.

2b. Carbon sequestration before a land-use transition if d = 9 or 10

If *j*'s *d* = 9 or 10 then *j* is managed as an even-aged 45-year rotation forestry operation. Therefore, assuming the operation on *j* has existed for at least 45 years, at any given time $1/45^{th}$ of the operation has just been replanted, $1/45^{th}$ of the operation has wood that is 1 year old, $1/45^{th}$ of the operation has wood that is 2 years old, etc. The last $1/45^{th}$ of the operation has wood that is 44 years old and will be cleared next year. Annual carbon sequestration on *j* in sub-land-use category *d* = 9 or 10 in various carbon pools are given by,

$$Wood_{jt+1} - Wood_{jt} \mid t+1 \le z = \sum_{a=0}^{44} WBMF(a, d_j, si_j)/45 - \sum_{a=0}^{44} WBMF(a, d_j, si_j)/45 = 0 \tag{25}$$

$$DWood_{jt+1} - DWood_{jt} \mid t+1 \le z = \sum_{a=0}^{44} DWMF(a, d_j, si_j)/45 - \sum_{a=0}^{44} DWMF(a, d_j, si_j)/45 = 0 \tag{26}$$

$$Under_{jt+1} - Under_{jt} \mid t+1 \le z = \sum_{a=0}^{44} UnderMF(a, d_j, si_j)/45 - \sum_{a=0}^{44} UnderMF(a, d_j, si_j)/45 = 0 \tag{27}$$

$$DDWood_{jt+1} - DDWood_{jt} \mid t+1 \le z = \sum_{a=0}^{44} DDWMF(a, d_j, si_j, Age_j)/45 - \sum_{a=0}^{44} DDWMF(a, d_j, si_j, Age_j)/45 \tag{28}$$

$$FFloor_{jt+1} - FFloor_{jt} \mid t+1 \le z = \sum_{a=0}^{44} FFMF(a, d_j, si_j, Age_j)/45 - \sum_{a=0}^{44} FFMF(a, d_j, si_j, Age_j)/45 \tag{29}$$

$$Sl_{jt+1} - Sl_{jt} \mid t+1 \le z = \sum_{a=0}^{44} SoilMF(a, d_j, si_j, soil_j, Age_j)/45 - \sum_{a=0}^{44} SoilMF(a, d_j, si_j, soil_j, Age_j)/45 \tag{30}$$

where:

- *WBMF* is an allometric equation that gives the metric tons of carbon per hectare stored in the wood of a managed forestry operation where the mix of soft wood (Douglas fir) and hard wood (Alder / Maple) is a function of *j*'s *d* (indicated by d_j) and *j*'s site index (si_j). In this case, if $d = 9$ the managed forestry operation is 96% Douglas fir and if $d = 10$ the managed forestry operation is 37% Douglas fir. The index *a* indicates the age of the tree stand.
- *DWMF* is an allometric equation that gives the metric tons of carbon per hectare stored in the standing dead wood of a managed forestry operation.
- *UnderMF* is an allometric equation that gives the metric tons of carbon per hectare stored in the forest understory of a managed forestry operation.
- *DDWMF* is an allometric equation that gives the metric tons of carbon per hectare stored in the downed dead wood of a managed forestry operation. *DDWMF* is also a function of the managed forestry operation's age as given by Age_j.
- *FFMF* is an allometric equation that gives the metric tons of carbon per hectare stored in the other debris on the forest floor of a managed forestry operation.
- *SoilMF* is an allometric formula that gives the metric tons of carbon per hectare stored in the soil of a managed forestry operation.

All allometric equations are from (*31*) and are specific to the Pacific Northwest, West region. As before, if $si_j = 0$ all allometric equation values in equations (25) through (30) are reduced by 5% and if $si_j = 1$ all allometric equation values are increased by 5%. After being in operation for 45 years, annual sequestration in the managed forestry pools *Wood*, *DWood*, and *Under* is equal to 0. That is not true for the other managed forestry pools where sequestration rates are a function of the operation's age and continue to change after 45 years of operation.

There are 2 sources of annual change in the *HWP* carbon pool on a parcel in managed forestry. The first is as before: if the parcel was in a forested land use on the Pre-Euroamerican settlement vegetation map (*12*) we assume that the virgin wood was clear-cut at some point in the past and that some of this carbon is still trapped in the model's initial year. See equation (24) for calculating $CCHWP_{jt+1} - CCHWP_{jt} \mid t+1 \le z$ for all $t \le z$. In this case, $Age_j = SoftAge_j = HardAge_j$ when using equation (24).

The last source of annual carbon sequestration in a managed forestry operation parcel comes from the change in the carbon content of harvested wood product removed due to the current operation.

$$HWPMF_{jt+1} - HWPMF_{jt} \mid t+1 \le z = \sum_{b=0}^{Age_j+t-45} HMF_j(b, d_j, si_j) \times WBMF(45, d_j, si_j)/45 - \sum_{b=0}^{Age_j+t-1-45} HMF_j(b, d_j, si_j) \times WBMF(45, d_j, si_j)/45 \quad (31)$$

where HMF_j is a Pacific Northwest, West region allometric equation that gives the fraction of carbon remaining in harvested wood b years after its removal. The index $b = 0$ indicates wood that has just been removed. See (*31*). As before, if $si_j = 0$ HMF_j values are reduced by 5% and if $si_j = 1$ HMF_j value are increased by 5%.

3. Annual carbon sequestration after a land-use transition

3a. Annual carbon sequestration after a land-use transition if $d \neq 9$ or 10 and $d^* \neq 9$ or 10

Annual sequestration in j during the time period $t \in (z, 50]$ given that d and d^* on j does not indicate managed forestry ($d \neq 9$ or 10 and $d^* \neq 9$ or 10) is addressed in this section.

After a parcel j experiences a land-use change from d to d^* that does not involve managed forestry there are 3 potential sources of sequestration. First, when j experiences a change from d to d^* not all d-related biomass on j is necessarily disturbed. For example, when a stand of fairly dense Douglas Fir is thinned to make room for homes, not all Douglas Fir is removed. From time $t = z$ to $t = 50$, the relative portions of undisturbed d-related softwood and hardwood on j are given by,

$$SUCC_j = SoftW_j^* \times CC_j^* \quad \text{if } SoftW_j^* \times CC_j^* < SoftW_j \times CC_j \quad (32)$$

$$SUCC_j = SoftW_j \times CC_j \quad \text{if } SoftW_j^* \times CC_j^* \ge SoftW_j \times CC_j \quad (33)$$

$$HUCC_j = HardW_j^* \times CC_j^* \quad \text{if } HardW_j^* \times CC_j^* < HardW_j \times CC_j \quad (34)$$

$$HUCC_j = HardW_j \times CC_j \quad \text{if } HardW_j^* \times CC_j^* \ge HardW_j \times CC_j \quad (35)$$

where an asterisk indicates the forest stand variables associated with the new sub-land-use category d^* and all other variables were assigned to each j according to its initial sub-land-use category d. The forest stand variables associated with j after a change to d^* are assigned randomly in the same manner as the stand variables were assigned to j give its d.

At the same time new forest stands may be planted in a parcel due to a change from d to d^*. In the year of transition ($t = z$), $SoftAge_j = HardAge_j = 0$ for any new forest stand on j and both variables' values increase by one each year. The relative portion of biomass that is planted on j at $t = z$ is given by,

$$SNCC_j = 0 \quad \text{if } SoftW_j^* \times CC_j^* < SoftW_j \times CC_j \quad (36)$$

$$SNCC_j = SoftW_j^* \times CC_j^* - SoftW_j \times CC_j \quad \text{if } SoftW_j^* \times CC_j^* \ge SoftW_j \times CC_j \quad (37)$$

$$HNCC_j = 0 \qquad \text{if } HardW_j^* \times CC_j^* < HardW_j \times CC_j \tag{38}$$

$$HNCC_j = HardW_j^* \times CC_j^* - HardW_j \times CC_j \qquad \text{if } HardW_j^* \times CC_j^* \geq HardW_j \times CC_j \tag{39}$$

Finally, portions of a forest stand may be removed when *j* transitions from *d* to *d**. The carbon in the portions of the *Wood, DWood, Under, DDWood, and FFloor* pools that are removed during a transition from *d* to *d** are lost instantly. At time $t = z$ the relative portion of wood removed from *j* at time $t = z$ is given by,

$$SRCC_j = SoftW_j \times CC_j - SoftW_j^* \times CC_j^* \qquad \text{if } SoftW_j^* \times CC_j^* < SoftW_j \times CC_j \tag{40}$$

$$SRCC_j = 0 \qquad \text{if } SoftW_j^* \times CC_j^* \geq SoftW_j \times CC_j \tag{41}$$

$$HRCC_j = HardW_j \times CC_j - HardW_j^* \times CC_j^* \qquad \text{if } HardW_j^* \times CC_j^* < HardW_j \times CC_j \tag{42}$$

$$HRCC_j = 0 \qquad \text{if } HardW_j^* \times CC_j^* \geq HardW_j \times CC_j \tag{43}$$

Given all this, the annual changes in the *Wood*, *DWood*, *Under*, *DDWood*, and *FFloor* pools after a change from *d* to *d** given that d and $d^* \neq 9$ or 10 are given by,

$$\begin{aligned} Wood_{jt+1} - Wood_{jt} \mid t \geq z = &\left(SWB\left(SoftAge_j + t + 1, \theta_j, si_j, E_j\right) \times SUCC_j\right) + \\ &\left(SWB\left(t - z + 1, \theta_j, si_j, E_j\right) \times SNCC_j\right) \\ &\left(HWB\left(HardAge_j + t + 1, \theta_j, si_j\right) \times HUCC_j\right) + \\ &\left(HWB\left(t - z + 1, \theta_j, si_j\right) \times HNCC_j\right) - \\ &\left(SWB\left(SoftAge_j + t, \theta_j, si_j, E_j\right) \times SUCC_j\right) - \\ &\left(SWB\left(t - z, \theta_j, si_j, E_j\right) \times SNCC_j\right) - \\ &\left(HWB\left(HardAge_j + t, \theta_j, si_j\right) \times HUCC_j\right) - \\ &\left(HWB\left(t - z, \theta_j, si_j\right) \times HNCC_j\right) \end{aligned} \tag{44}$$

$$\begin{aligned} DWood_{jt+1} - DWood_{jt} \mid t \geq z = &\left(SDW\left(SoftAge_j + t + 1, \theta_j, si_j, E_j\right) \times SUCC_j\right) + \\ &\left(SDW\left(t - z + 1, \theta_j, si_j, E_j\right) \times SNCC_j\right) \\ &\left(HDW\left(HardAge_j + t + 1, \theta_j, si_j\right) \times HUCC_j\right) + \\ &\left(HDW\left(t - z + 1, \theta_j, si_j\right) \times HNCC_j\right) - \\ &\left(SDW\left(SoftAge_j + t, \theta_j, si_j, E_j\right) \times SUCC_j\right) - \\ &\left(SDW\left(t - z, \theta_j, si_j, E_j\right) \times SNCC_j\right) - \\ &\left(HDW\left(HardAge_j + t, \theta_j, si_j\right) \times HUCC_j\right) - \\ &\left(HDW\left(t - z, \theta_j, si_j\right) \times HNCC_j\right) \end{aligned} \tag{45}$$

$$\begin{aligned} Under_{jt+1} - Under_{jt} \mid t \geq z = &\left(SUnder\left(SoftAge_j + t + 1, \theta_j, si_j, E_j\right) \times SUCC_j\right) + \\ &\left(SUnder\left(t - z + 1, \theta_j, si_j, E_j\right) \times SNCC_j\right) \\ &\left(HUnder\left(HardAge_j + t + 1, \theta_j, si_j\right) \times HUCC_j\right) + \\ &\left(HUnder\left(t - z + 1, \theta_j, si_j\right) \times HNCC_j\right) - \\ &\left(SUnder\left(SoftAge_j + t, \theta_j, si_j, E_j\right) \times SUCC_j\right) - \\ &\left(SUnder\left(t - z, \theta_j, si_j, E_j\right) \times SNCC_j\right) - \\ &\left(HUnder\left(HardAge_j + t, \theta_j, si_j\right) \times HUCC_j\right) - \\ &\left(HUnder\left(t - z, \theta_j, si_j\right) \times HNCC_j\right) \end{aligned} \tag{46}$$

$$
\begin{aligned}
DDWood_{jt+1} - DDWood_{jt} \mid t \geq z = &\left(SDDW\left(SoftAge_j + t + 1, \theta_j, si_j, E_j\right) \times SUCC_j\right) + \\
&\left(SDDW\left(t - z + 1, \theta_j, si_j, E_j\right) \times SNCC_j\right) \\
&\left(HDDW\left(HardAge_j + t + 1, \theta_j, si_j\right) \times HUCC_j\right) + \\
&\left(HDDW\left(t - z + 1, \theta_j, si_j\right) \times HNCC_j\right) - \\
&\left(SDDW\left(SoftAge_j + t, \theta_j, si_j, E_j\right) \times SUCC_j\right) - \\
&\left(SDDW\left(t - z, \theta_j, si_j, E_j\right) \times SNCC_j\right) - \\
&\left(HDDW\left(HardAge_j + t, \theta_j, si_j\right) \times HUCC_j\right) - \\
&\left(HDDW\left(t - z, \theta_j, si_j\right) \times HNCC_j\right)
\end{aligned} \tag{47}
$$

$$
\begin{aligned}
FFloor_{jt+1} - FFloor_{jt} \mid t \geq z = &\left(SFF\left(SoftAge_j + t + 1, \theta_j, si_j, E_j\right) \times SUCC_j\right) + \\
&\left(SFF\left(t - z + 1, \theta_j, si_j, E_j\right) \times SNCC_j\right) \\
&\left(HFF\left(HardAge_j + t + 1, \theta_j, si_j\right) \times HUCC_j\right) + \\
&\left(HFF\left(t - z + 1, \theta_j, si_j\right) \times HNCC_j\right) - \\
&\left(SFF\left(SoftAge_j + t, \theta_j, si_j, E_j\right) \times SUCC_j\right) - \\
&\left(SFF\left(t - z, \theta_j, si_j, E_j\right) \times SNCC_j\right) - \\
&\left(HFF\left(HardAge_j + t, \theta_j, si_j\right) \times HUCC_j\right) - \\
&\left(HFF\left(t - z, \theta_j, si_j\right) \times HNCC_j\right)
\end{aligned} \tag{48}
$$

where all equations and variables are as before. The only exceptions to these equations hold when $t = z$: values for $Wood_{jz}$, $DWood_{jz}$, $DDWood_{jz}$, $Under_{jz}$, and $FFloor_{jz}$ are given by equations (18) through (22).

If $d^* \in [1,8]$, $d^* \in [11,28]$ or $d^* \in [39,43]$ then the annual change in soil carbon from $t = z$ to $t = 50$ is given by,

$$
Sl_{jt+1} - Sl_{jt} \mid t \geq z = \begin{cases} \left(SoilMass_{d^*} - Sl_{jz}\right) / SoilEqu_{d^*} & \text{if } t - z \leq SoilEqu_{d^*} \\ 0 & \text{if } t - z > SoilEqu_{d^*} \end{cases} \tag{49}
$$

where $SoilMass_{d^*}$ is the equilibrium soil carbon in tons per hectare associated with land-use d^*, Sl_{jz} is the metric tons per hectare of carbon in j's soil in the year of transition from d to d^*, and $SoilEqu_{d^*}$ is the number of years after a land-use transition to d^* that it takes to reach soil carbon equilibrium. The values of $SoilMass_{d^*}$ and $SoilEqu_{d^*}$ are given in SI Table 13.

If $d^* \in [29,38]$ then the annual change in soil carbon from $t = z$ to $t = 50$ is given by,

$$
Sl_{jt+1} - Sl_{jt} \mid t \geq z = \begin{cases} \left(SSoil\left(SoftAge_j^* + t + 1, \theta_j, si_j, soil_j\right) \times SoftW_j^*\right) + \\ \left(HSoil\left(HardAge_j^* + t + 1, \theta_j, si_j, soil_j\right) \times HardW_j^*\right) - Sl_{jz} & \text{if } t = z \\ \\ \left(SSoil\left(SoftAge_j^* + t + 1, \theta_j, si_j, soil_j\right) \times SoftW_j^*\right) + \\ \left(HSoil\left(HardAge_j^* + t + 1, \theta_j, si_j, soil_j\right) \times HardW_j^*\right) - \\ \left(SSoil\left(SoftAge_j^* + t, \theta_j, si_j, soil_j\right) \times SoftW_j^*\right) \\ \left(HSoil\left(HardAge_j^* + t, \theta_j, si_j, soil_j\right) \times HardW_j^*\right) & \text{if } t > z \end{cases} \tag{50}
$$

The annual carbon sequestration in non-tree root mass from $t = z$ to $t = T$ is given by,

$$
Rt_{jt+1} - Rt_{jt} \mid t \geq z = \begin{cases} \left(RootMass_{d^*} - Rt_{jz}\right) / RootEqu_{d^*} & \text{if } t - z \leq RootEqu_{d^*} \\ 0 & \text{if } t - z > RootEqu_{d^*} \end{cases} \tag{51}
$$

where $RootMass_{d^*}$ is the equilibrium non-tree root mass carbon associated with land-use d^*, $RootEqu_{d^*}$ is the number of years after land-use transition it takes to reach non-tree root mass carbon equilibrium on land use d^*. The values of $RootMass_{d^*}$ and $RootEqu_{d^*}$ are given in SI Table 14.

The annual change in other biomass carbon from $t = z$ to $t = T$ is given by,

$$OthBiomass_{jt+1} - OthBiomass_{jt} \mid t \geq z =$$

$$\begin{cases} OrchardBiomass_{d*}/(T-z) & \text{if } OrchardBiomass_j = 0 \text{ and } d \neq 1 \text{ or } 2 \\ -OrchardBiomass_j & \text{if } OrchardBiomass_j > 0,\ t = z,\ d^* \neq 1 \text{ or } 2 \\ 0 & \text{otherwise} \end{cases} \quad (52)$$

If j experienced a change in the $CCHWP_j$ pool from $t = 1$ to $t = z$ changes in the pool are tracked in the years $t \geq z$ as well. In addition, an additional pool of carbon in clear-cut harvested wood product may be produced on each j in the years $t \geq z$. This second pool of clear cut carbon is given by,

$$\begin{aligned} CCSHWP_{jt+1} - CCSHWP_{jt} \mid t \geq z = & \left(SHWP(t-z+1, si_j) \times SWB(SoftAge_j + z, \theta_j, si_j, E_j) \times SRCC_j\right) + \\ & \left(HHWP(t-z+1, si_j) \times HWB(HardAge_j + z, \theta_j, si_j, E_j) \times HRCC_j\right) - \\ & \left(SHWP(t-z, si_j) \times SWB(SoftAge_j + z, \theta_j, si_j, E_j) \times SRCC_j\right) - \\ & \left(HHWP(t-z, si_j) \times HWB(HardAge_j + z, \theta_j, si_j, E_j) \times HRCC_j\right) \end{aligned} \quad (53)$$

where $CCSHWP_j$ indicates the second pool and all other variables are as before. The only exception to equation (53) is when $t = z$. At this point in time $CCSHWP_j = 0$.

3b. Annual carbon sequestration after a land-use transition if d = 9 or 10

If a parcel is in managed forestry (d = 9 or 10) and transitions to some $d^* \in [29,38]$ (i.e., a forested land use that is not managed for timber) then the following annual carbon sequestration equations hold,

$$\begin{aligned} Wood_{jt+1} - Wood_{jt} \mid z \geq t = \frac{1}{45}\Big[\textstyle\sum_{s=1}^{45} & \left(SWB(s+t-z, \theta_j, si_j, E_j) \times SoftW_j^* \times CC_j\right) + \\ & \left(HWB(s+t-z, \theta_j, si_j) \times HardW_j^* \times CC_j\right) - \\ & \left(SWB(s-1+t-z, \theta_j, si_j, E_j) \times SoftW_j^* \times CC_j\right) - \\ & \left(HWB(s-1+t-z, \theta_j, si_j) \times HardW_j^* \times CC_j\right)\Big] \end{aligned} \quad (54)$$

$$\begin{aligned} DWood_{jt+1} - DWood_{jt} \mid t \geq z = \frac{1}{45}\Big[\textstyle\sum_{s=1}^{45} & \left(SDW(s+t-z, \theta_j, si_j, E_j) \times SoftW_j^* \times CC_j\right) + \\ & \left(HDW(s+t-z, \theta_j, si_j) \times HardW_j^* \times CC_j\right) - \\ & \left(SDW(s-1+t-z, \theta_j, si_j, E_j) \times SoftW_j^* \times CC_j\right) - \\ & \left(HDW(s-1+t-z, \theta_j, si_j) \times HardW_j^* \times CC_j\right)\Big] \end{aligned} \quad (55)$$

$$\begin{aligned} Under_{jt+1} - Under_{jt} \mid t \geq z = \frac{1}{45}\Big[\textstyle\sum_{s=1}^{45} & \left(SUnder(s+t-z, \theta_j, si_j, E_j) \times SoftW_j^* \times CC_j\right) + \\ & \left(HUnder(s+t-z, \theta_j, si_j) \times HardW_j^* \times CC_j\right) - \\ & \left(SUnder(s-1+t-z, \theta_j, si_j, E_j) \times SoftW_j^* \times CC_j\right) - \\ & \left(HUnder(s-1+t-z, \theta_j, si_j) \times HardW_j^* \times CC_j\right)\Big] \end{aligned} \quad (56)$$

$$\begin{aligned} DDWood_{jt+1} - DDWood_{jt} \mid t \geq z = \frac{1}{45}\Big[\textstyle\sum_{s=1}^{45} & \left(SDDW(s+t-z, \theta_j, si_j, E_j) \times SoftW_j^* \times CC_j\right) + \\ & \left(HDDW(s+t-z, \theta_j, si_j) \times HardW_j^* \times CC_j\right) - \\ & \left(SDDW(s-1+t-z, \theta_j, si_j, E_j) \times SoftW_j^* \times CC_j\right) - \\ & \left(HDDW(s-1+t-z, \theta_j, si_j) \times HardW_j^* \times CC_j\right)\Big] \end{aligned} \quad (57)$$

$$FFloor_{jt+1} - FFloor_{jt} \mid t \geq z = \frac{1}{45}\Big[\sum_{s=1}^{45}\big(SFF(s+t-z,\theta_j,si_j,E_j)\times SoftW_j^* \times CC_j\big)+ \big(HFF(s+t-z,\theta_j,si_j)\times HardW_j^* \times CC_j\big)- \big(SFF(s-1+t-z,\theta_j,si_j,E_j)\times SoftW_j^* \times CC_j\big)- \big(HFF(s-1+t-z,\theta_j,si_j)\times HardW_j^* \times CC_j\big)\Big] \quad (58)$$

where all functions and variables are as before. The only exceptions to these equations hold when $t = z$: values for $Wood_{jz}$, $DWood_{jz}$, $DDWood_{jz}$, $Under_{jz}$, and $FFloor_{jz}$ are given by equations (25) through (29).

If a parcel is in managed forestry (d = 9 or 10) and transitions to some $d^* \in [1,8]$, $d^* \in [11,28]$, or $d^* \in [39,43]$ then the managed forest is clear-cut at $t = z$ and is replanted with the mix and cover density of trees associated with d^*: $SoftW_j^*$, $HardW_j^*$, and CC_j^*. The year of the transition from d to d^* ($t = z$), the trees on j have $SoftAge_j = HardAge_j = 0$. Use these new variables with equations (18) through (22) to determine annual sequestration in the $Wood_j$, $DWood_j$, $DDWood_j$, $Under_j$, and $FFloor_j$ carbon pools. The only exceptions to these equations hold when $t = z$: values for $Wood_{jz}$, $DWood_{jz}$, $DDWood_{jz}$, $Under_{jz}$, and $FFloor_{jz}$ are given by equations (25) through (29).

If $d^* \in [1,8]$, $d^* \in [11,28]$, or $d^* \in [39,43]$ then the annual change in soil carbon from $t = z$ to $t = T$ is given by,

$$Sl_{jt+1} - Sl_{jt} \mid t \geq z = \begin{cases} \left(SoilMass_{d^*} - Sl_{jz}\right)/SoilEqu_{d^*} & if\ t - z \leq SoilEqu_{d^*} \\ 0 & if\ t - z > SoilEqu_{d^*} \end{cases} \quad (59)$$

where $SoilMass_{d^*}$ is the equilibrium soil carbon associated with land-use d^*, Sl_{jz} is the amount of carbon in j's soil in the year of transition from d = 9 or 10 (use equation (30)) to d^*, and $SoilEqu_{d^*}$ is the number of years after a land-use transition to d^* that it takes to reach soil carbon equilibrium.

If $d^* \in [29,38]$ then the annual change in soil carbon from $t = z$ to $t = T$ is given by,

$$Sl_{jt+1} - Sl_{jt} \mid t \geq z = \begin{cases} \frac{1}{45}\Big[\sum_{s=1}^{45}\big(SSoil(s,\theta_j,si_j,soil_j)\times SoftW_j^*\big)+ \big(HSoil(s,\theta_j,si_j,soil_j)\times HardW_j^*\big)- Sl_{jz} & \text{if } t = z \\ \frac{1}{45}\Big[\sum_{s=1}^{45}\big(SSoil(s+t-z,\theta_j,si_j,soil_j)\times SoftW_j^*\big)+ \big(HSoil(s+t-z,\theta_j,si_j,soil_j)\times HardW_j^*\big)- \big(SSoil(s-1+t-z,\theta_j,si_j,soil_j)\times SoftW_j^*\big)- \big(HSoil(s-1+t-z,\theta_j,si_j,soil_j)\times HardW_j^*\big)\Big] & \text{if } t > z \end{cases} \quad (60)$$

where Sl_{jz} is determined using equation (30). If j's $soil_j$ = 0 all allometric equation values in equation (60) are reduced by 5% and if $soil_j$ = 1 all allometric equation values in equation (60) are increased by 5%.

The annual sequestration in non-tree root mass for the period $t \geq z$ is,

$$Rt_{jt+1} - Rt_{jt} \mid t \geq z = \begin{cases} RootMass_{d^*}/RootEqu_{d^*} & if\ t - z \leq RootEqu_{d^*} \\ 0 & if\ t - z > RootEqu_{d^*} \end{cases} \quad (61)$$

where all variables are as before. Further, the annual change in other biomass carbon from $t = z$ to $t = T$ is given by,

$$OthBiomass_{jt+1} - OthBiomass_{jt} \mid t \geq z = OrchardBiomass_{d^*}/(T - z) \quad (62)$$

where all variables are as before.

If j experienced a change in the $CCHWP_j$ pool from $t = 1$ to $t = z$ it is tracked in the years $t \geq z$. If the managed forestry operation is clear-cut, an additional $CCHWP_j$ pool is generate for the years $t \geq z$:

$$CCSHWP_{jt+1} - CCSHWP_{jt} \mid t \geq z = \left(HMF_j\left(t - z + 1, si_j\right) \times \sum_{g=0}^{44} WBMF\left(g, d_j, si_j\right) \right) \Big/ 45 - \left(HMF_j\left(t - z, si_j\right) \times \sum_{g=0}^{44} WBMF\left(g, d_j, si_j\right) \right) \Big/ 45 \quad (63)$$

where $CCSHWP_j$ indicates the second pool and all variables are as before. The only exception to equation (63) is when $t = z$. At this point $CCSHWP_{jz} = 0$. Note that for every $t > z$, $CCSHWP_{jt+1}$ - $CCSHWP_{jt} < 0$.

Finally, the portions of the carbon trapped in forest product from the previous managed forestry operation continues to be stored in product for the years $t = z$ to $t = 50$. Annual sequestration in this pool is given by the following,

$$HWPMF_{jt+1} - HWPMF_{jt} \mid t \geq z = \left(\sum_{b=t-z+1}^{Age_j+t-45} HMF_j\left(b, si_j\right) \times WBMF\left(44, d_j, si_j\right) \right) / 45 - \left(\sum_{b=t-z}^{Age_j+t-45} HMF_j\left(b, si_j\right) \times WBMF\left(44, d_j, si_j\right) \right) / 45 \quad (64)$$

The only exception to equation (64) is when $t = z$. At this point $HWPMF_{jz} = 0$. Note that for every $t > z$, $HWPMF_{jt+1}$ - $HWPMF_{jt} < 0$.

3c. Annual carbon sequestration after a land-use transition if d^* = 9 or 10

If a parcel initially is in some sub-land-use category other than managed forestry ($d \neq 9$ or 10) and transitions to managed forestry ($d^* = 9$ or 10) then any trees on the parcel are clear cut at $t = z$ and trees are planted thereafter to set up an even-age rotation of 45 years. In other words, the year after the clear cut, $1/45^{th}$ of the parcel or hectare has a managed forest tree stand that is 1 years old, two years after the cut $1/45^{th}$ of the parcel or hectare has a managed forest tree stand that is 2 years old and $1/45^{th}$ of the parcel or hectare has a managed forest tree stand that is 1 years old, etc. The first harvest of $1/45^{th}$ of the parcel or hectare does not occur for 45 years after $t = z$. The mix of softwood, hardwood, and canopy coverage - $SoftW_j^*$, $HardW_j^*$, and CC_j^* - for the managed forest depends on whether $d^* = 9$ or $d^* = 10$.

$$Wood_{jt+1} - Wood_{jt} \mid t \geq z = \sum_{a=1}^{t-z+1} WBMF\left(a, d_j, si_j\right) / 45 - \sum_{a=1}^{t-z} WBMF\left(a, d_j, si_j\right) / 45 = 0 \quad (65)$$

$$DWood_{jt+1} - DWood_{jt} \mid t \geq z = \sum_{a=1}^{t-z+1} DWMF\left(a, d_j, si_j\right) / 45 - \sum_{a=1}^{t-z} DWMF\left(a, d_j, si_j\right) / 45 = 0 \quad (66)$$

$$Under_{jt+1} - Under_{jt} \mid t \geq z = \sum_{a=1}^{t-z+1} UnderMF\left(a, d_j, si_j\right) / 45 - \sum_{a=1}^{t-z} UnderMF\left(a, d_j, si_j\right) / 45 = 0 \quad (67)$$

$$DDWood_{jt+1} - DDWood_{jt} \mid t \geq z = \sum_{a=1}^{t-z+1} DDWMF\left(a, d_j, si_j, Age_j\right) / 45 - \sum_{a=1}^{t-z} DDWMF\left(a, d_j, si_j, Age_j\right) / 45 \quad (68)$$

$$FFloor_{jt+1} - FFloor_{jt} \mid t \geq z = \sum_{a=1}^{t-z+1} FFMF\left(a, d_j, si_j, Age_j\right)/45 - \sum_{a=1}^{t-z} FFMF\left(a, d_j, si_j, Age_j\right)/45 \tag{69}$$

$$Sl_{jt+1} - Sl_{jt} \mid t \geq z = \sum_{a=1}^{50-z} SoilMF\left(a, d_j, si_j, soil_j, Age_j\right)/45 - \sum_{a=0}^{50-z-1} SoilMF\left(a, d_j, si_j, soil_j, Age_j\right)/45 \tag{70}$$

where all functions and variables are as before. The only exceptions to these equations hold when $t = z$: values for $Wood_{jz}$, $DWood_{jz}$, $DDWood_{jz}$, $Under_{jz}$, $FFloor_{jz}$, and Sl_{jz} are given by equations (18) through (23).

If there was any carbon stored in non-tree root mass at the time of transition from d to $d^* = 9$ or $d^*= 10$, it is instantly lost. The annual change in non-tree root mass carbon from $t = z$ to $t = T$ is given by,

$$Rt_{jt+1} - Rt_{jt} \mid t \geq z = \begin{cases} -Rt_{jz} & \text{if } t = z \\ 0 & \text{otherwise} \end{cases} \tag{71}$$

If there was any carbon stored in orchard biomass at the time of transition from d to $d^* = 9$ or $d^*= 10$, it is instantly lost.

$$OthBiomass_{jt+1} - OthBiomass_{jt} \mid t \geq z = \begin{cases} -OrchardBiomass_{jz} & \text{if } t = z \\ 0 & \text{otherwise} \end{cases} \tag{72}$$

If j experienced a change in the $CCHWP_j$ pool from $t = 1$ to $t =$ z changes are tracked in the years $t \geq z$ as well. If a forest is clear-cut to prepare j for a managed forestry operation, an additional $CCHWP_j$ pool is generated in the years $t \geq z$:

$$\begin{aligned} CCHWP_{jt+1} - CCHWP_{jt} \mid t \geq z = &\left(SHWP\left(t-z+1, si_j\right) \times SWB\left(SoftAge_j + z, \theta_j, si_j, E_j\right) \times SoftW_j \times CC_j\right) + \\ &\left(HHWP\left(t-z+1, si_j\right) \times HWB\left(HardAge_j + z, \theta_j, si_j, E_j\right) \times HardW_j \times CC_j\right) - \\ &\left(SHWP\left(t-z, si_j\right) \times SWB\left(SoftAge_j + z, \theta_j, si_j, E_j\right) \times SoftW_j \times CC_j\right) - \\ &\left(HHWP\left(t-z, si_j\right) \times HWB\left(HardAge_j + z, \theta_j, si_j, E_j\right) \times HardW_j \times CC_j\right) \end{aligned} \tag{73}$$

where $CCSHWP_j$ indicates the second pool. The only exception to equation (73) is when $t = z$. At this point in time $CCSHWP = 0$.

Finally, if the year of transition from d to $d^* = 9$ or 10 happens early enough in the modeling time frame, the new managed forestry operation on j may begin to produce harvested product with trapped carbon before $t = 50$. Annual sequestration in this pool is given by the following,

$$HWPMF_{jt+1} - HWPMF_{jt} \mid t - 45 \geq z = \sum_{b=1}^{t-45} HMF_j\left(b, si_j\right) \times WBMF\left(45, d_j, si_j\right)/45 - \sum_{b=1}^{t-46} HMF_j\left(b, si_j\right) \times WBMF\left(45, d_j, si_j\right)/45 \tag{74}$$

4. Model simulation

To run the model each parcel j was randomly assigned values for the variables discussed above according to its sub-land-use categories d and d^*. Next, each parcel was randomly assigned a land use transition time of z from a uniform range of 2 to 30. The model assumes a uniform distribution for all variables.

Next, the annual change in each carbon pool on each j was calculated for each potential land use transition from i to $k = 1,\ldots,14$ where i indicates j's land use on the current land-use pattern, k indexes the terminal land use on j and $t = z$ is the time of transition. Recall that for each i and k on j there is a unique sub-land-use category d and d^*, respectively.

Given these random assignments, the discounted per hectare carbon sequestration in each pool on j for each potential land-use transition was determined using equations (29)-(37). Then the total discounted carbon sequestration on j for a particular land-use transition was determined by summing across all pools for that land-use change and converting the summed per hectare value to a parcel-wide value. The total discounted carbon sequestration on j is for all 14 potential land-use changes, including $i = k$ (and thus $d = d^*$) was gathered in an 8176 x 14 matrix of discounted carbon sequestration values.

The modeling process described above was run 25 times. The twenty-five 8176 x 14 matrices were used to find an average sequestration matrix. This 8176 x 14 lookup table of average sequestration rates was used to find the landscape carbon sequestration value for a baseline or policy-induced land-use pattern. The complex model landscape-level results are normalized by dividing by the maximum carbon sequestration potential on the landscape. This look-up table of average sequestration rates was also used when determining the complex model efficiency frontier approximating optimization routines, described in equations (83)-(113), $\overline{C}_{jk}$, the average complex model carbon sequestration value on parcel j in terminal land use k, is represented by V_j^i where i in this case is equivalent to k.

Simple Species Conservation Model

The simple species conservation model determines the average proportion of potential habitat that is suitable for the modeled terrestrial vertebrates on a given land-use pattern. Let $B \in [0,1]$ indicate the average fraction of the modeled species' geographic range that is in suitable habitat on land-use pattern $\hat{\mathbf{X}}$.

$$B = \frac{1}{37}\sum_{s=1}^{37}\frac{\left(\sum_{j=1}^{8176} H_{sj} A_j \left(\sum_{i=1}^{14} \hat{X}_j^i C_{si}\right)\right)}{\left(\sum_{j=1}^{8176} H_{sj} A_j\right)} \tag{75}$$

where $s = 1,\ldots,37$ indexes the 37 terrestrial vertebrate species modeled on the landscape, H_{sj} is a binary variable that indicates whether j is in the geographic range of species s, A_j is the area of parcel j, and C_{si} indicates the compatibility of species s with land-use type i. A species' compatibility score refers to the habitat's suitability for breeding and feeding activities, where 1 indicates that the land cover is prime habitat, 0.5 indicates the land cover is marginally suitable, and 0 indicates that the species does not breed or feed in that land cover. The 37 species modeled in this analysis were determined to have low persistence probabilities on the 1990 land-use pattern in the Willamette Basin and/or were sensitive to slight changes in mix and amount of conserved land cover in the Basin (*2*). See SI Fig. 3 for geographic range maps of each modeled species and SI Table 15 for C_{si} for each s,i combination.

The numerator of the fraction in equation (74) calculates the amount of effective habitat area for species s on land-use pattern $\hat{\mathbf{X}}$, which can range from 0 to $\sum_{j=1}^{8176} H_{sj} A_j$. The denominator of the fraction in equation (75) gives the maximum potential habitat area for species s on $\hat{\mathbf{X}}$. The fraction in (75) gives the portion of geographic range for species s that is in suitable habitat. By summing the fraction in equation (75) across all s and then dividing by the total number of species, 37, we obtain the average proportion of potential habitat that is suitable for the modeled species.

Instead of reporting the fraction of potential habitat area that is in suitable habitat on $\hat{\mathbf{X}}$, the simple species conservation model could report the average number of hectares in suitable habitat for the modeled species. What is the effect of the normalization in the simple species conservation model (i.e., dividing by $\sum_{j=1}^{8176} H_{sj} A_j$)? Species with very large geographic ranges will tend to have low normalized scores while species with small geographic ranges will have a much greater range in normalized values. Further, the normalized scores of small range species will experience a greater increase per unit of additional habitat then the normalized score of large range species after a similar one-unit increase. Given this bias, why do we normalize? Assume we did not normalize. Further, assume that species 1 had 10 hectares of effective habitat and species 2 has 100 hectares of effective habitat. This does not necessarily mean that species 2 is almost 10 times better off than species 1. Species 1 may have compatible land cover in its whole geographic range and species 2 may only have compatible land cover in a fraction of its geographic range. In this case, species 1 may have a better probability of long term persistence than species 2. Thus, it could be argued that species 1 should have a higher conservation score than species 2 despite the difference in habitat space on the landscape. Therefore, despite the bias in normalizing, we do it because first of all, we assume that H_{sj} describes the species distribution in the Pre-Euroamerican settlement era (a reference point) and that species that do not have compatible land cover in a significant part of their niche space are at great risk for extinction (*33*). Therefore, no matter the species range size, low *B* values are troublesome. Secondly, range-restricted species tend to have higher extinction risks than large-range species (*34*, *35*). Therefore, making equation (75) more sensitive to the changes in habitat area for range-restricted species may be appropriate given their higher extinction risks.

The simple model *B* statistic is similar to a statistic proposed by (*33*) to measure biodiversity loss under the Convention on Biological Diversity. The main difference is that (*33*) translate their statistic into relative richness of species. See source (*35*) for earlier work on *B*-like statistics.

The Complex Species Conservation Model

The complex species conservation model is described in (*36*) and (*2*). In this case the species conservation score of interest is the number of species that are expected to be sustained indefinitely on a land-use pattern. First, the complex species conservation model calculates a landscape score for each species on land-use pattern $\hat{\mathbf{X}}$. A species landscape score is a function of 1) species' breeding and feeding area requirements (given by AR_s); 2) species' ability to disperse across the landscape (given by α_s); and 3) the amount and configuration of suitable habitat on $\hat{\mathbf{X}}$. Second, each species' landscape score is then converted to a long-term persistence probability by fitting its landscape score to a saturating function. Finally, the persistence probabilities for all 37 species are aggregated and then divided by 37 to give a relative score between 0 and 1. See SI Table 16 for the AR_s values used in this research. See SI Table 17 for the α_s values used in this research.

Efficiency frontiers

1. Simple models efficiency frontier

A point on the simple models efficiency frontier is found by defining a land-use pattern $\hat{\mathbf{X}}$ that solves the following,

$$\max_{\hat{x}}\left(\frac{1}{37}\sum_{s=1}^{37}\frac{\left(\sum_{j=1}^{8176}H_{sj}A_j\left(\sum_{i=1}^{14}\hat{X}_j^i C_{sk}\right)\right)}{\left(\sum_{j=1}^{8176}H_{sj}A_j\right)}\right) \tag{76}$$

subject to

$$\sum_{j=1}^{8176}\sum_{i=1}^{14}P_j^i\left(A_j \times 2.471\right)\hat{X}_j^i \le D \tag{77}$$

$$\frac{\left(\sum_{j=1}^{8176}\sum_{i=1}^{14}\overline{G}_j^i A_j \hat{X}_j^i\right)}{\sum_{j=1}^{8176}A_j \max\left\{\overline{G}_j^1,\ldots,\overline{G}_j^{14}\right\}} \ge E \tag{78}$$

$$\sum_{i=1}^{14}M_j^i\hat{X}_j^i = 1 \qquad \forall j \tag{79}$$

$$\sum_{i=1}^{14}\hat{X}_j^i = 1 \qquad \forall j \tag{80}$$

$$\hat{X}_j^i = \{0,1\} \qquad \forall i,j \tag{81}$$

$$M_j^i = \{0,1\} \qquad \forall i,j \tag{82}$$

where P_j^i is the annual per acre price of choosing land cover *i* on *j*, *D* is the conservation budget, $\hat{G}_j^i$ is the carbon sequestered (per hectare) on parcel *j* over 50 years by converting to $\hat{X}_j^i$ given X_j^i, *E* is any fixed level of the fraction of carbon sequestered on the landscape over 50 years (ranging from 0 to 1, where *E* = 1 represents the maximum possible carbon that can be sequestered on the landscape), and M_j^i is equal to 1 if *j* can be placed in $\hat{X}_j^i$ and equals 0 otherwise.

The objective function (76) is the simple species conservation model. $\hat{G}_j^i$ is estimated using the simple carbon sequestration model. The denominator of equation (78) gives the maximum carbon sequestration potential on the landscape. Thus equation (78) ranges from 0 to 1.

P_j^i is greater than 0 if and only if $\hat{X}_j^i \ne X_j^i$ and the change was induced by a conservation policy where X_j^i indicates the initial land use on *j* (given by the current land-use pattern) and $\hat{X}_j^i$ is the terminal land use on *j* (recall that in a baseline simulation $\hat{X}_j^i$ may not equal X_j^i for reasons other than a conservation policy). In such cases, P_j^i is equal to parcel *j*'s per acre WTA for a conservation contract. A parcel *j* that accepts a conservation contract is assigned its Pre-Euroamerican settlement vegetation cover type (*12*). The factor 2.471 converts the area of *j* from hectares to acres.

By setting *D* equal to the policy budget level and solving the above for various levels of $E \in [0,1]$ we can trace a species conservation-carbon sequestration efficiency frontier for the given *D*.

2. The complex models efficiency frontier

The complex species conservation model is discrete and non-linear. Therefore, finding the exact species conservation-carbon sequestration efficiency frontier with the complex species conservation model is computationally difficult. Following (*2*), we find candidate frontier points by solving three optimization problems that approximate the complex models efficiency problem and run all candidate land-use patterns through the complex species conservation model. (The normalized carbon sequestration values do not have to be re-valued since we can use the complex carbon model in all three approximating optimization models). From the complete set of re-calculated candidate points we choose the subset of points that form the outer envelop on a species conservation-carbon sequestration graph.

2a. The 1st approximating optimization problem

$$\max_{\hat{\mathbf{X}}} \sum_{s=1}^{37} \sum_{j=1}^{8176} H_{sj} A_j \left(\sum_{i=1}^{14} \hat{X}_j^i C_{si} \right) \tag{83}$$

subject to

$$\sum_{j=1}^{8176} \sum_{i=1}^{14} P_j^i A_j \hat{X}_j^i \leq D \tag{84}$$

$$\frac{\left(\sum_{j=1}^{8176} \sum_{i=1}^{14} V_j^i A_j \hat{X}_j^i \right)}{\sum_{j=1}^{8176} A_j \max\left\{ V_j^1, \ldots, V_j^{14} \right\}} \geq E \tag{85}$$

$$\sum_{i=1}^{15} M_j^i \hat{X}_j^i = 1 \qquad \forall j \tag{86}$$

$$\sum_{i=1}^{15} \hat{X}_j^i = 1 \qquad \forall j \tag{87}$$

$$\hat{X}_j^i = \{0,1\} \qquad \forall i, j \tag{88}$$

$$M_j^i = \{0,1\} \qquad \forall i, j \tag{89}$$

where V_j^i is the amount of carbon sequestered (per hectare) on parcel *j* over 50 years by converting to $\hat{X}_j^i$ given X_j^i and all other variables are as before. V_j^i is determined using the complex carbon sequestration model. In this model each additional hectare of effective habitat produced for any species on a land-use pattern $\hat{\mathbf{X}}$ increases the objective function by 1 unit.

2b. The 2nd approximating optimization problem

$$\max_{\hat{\mathbf{X}}} \sum_{s=1}^{37} y_s \tag{90}$$

subject to

$$y_s \le \sum_{j=1}^{8176} \frac{H_{sj} A_j \left(\sum_{i=1}^{14} \hat{X}_j^i C_{si}\right)}{AR_s} \qquad s = 1,\ldots,37 \tag{91}$$

$$y_s \le \lambda \qquad s = 1,\ldots,37 \tag{92}$$

$$\sum_{j=1}^{8176} \sum_{i=1}^{14} P_j^i A_j \hat{X}_j^i \le D \tag{93}$$

$$\frac{\left(\sum_{j=1}^{8176} \sum_{i=1}^{14} V_j^i A_j \hat{X}_j^i\right)}{\sum_{j=1}^{8176} A_j \max\left\{V_j^1,\ldots,V_j^{14}\right\}} \ge E \tag{94}$$

$$\sum_{i=1}^{14} M_j^i \hat{X}_j^i = 1 \qquad \forall j \tag{95}$$

$$\sum_{i=1}^{14} \hat{X}_j^i = 1 \qquad \forall j \tag{96}$$

$$\hat{X}_j^i = \{0,1\} \qquad \forall i, j \tag{97}$$

$$M_j^i = \{0,1\} \qquad \forall i, j \tag{98}$$

where AR_s is the area (in hectares) needed to support a breeding pair of species s , λ varies between 1000 and 2000, and all other variables are as before. In equations (90)-(92) y_s indicates the number of breeding pairs of s that are supported on $\hat{\mathbf{X}}$. However, unlike the complex species conservation model, y_s is not a function of habitat spatial pattern in this approximating optimization problem, just the amount of habitat. To avoid solutions that increase the number of breeding pairs to a very high level for a few species and keep the breeding pair counts for other species very low, an upper limit is placed on the number of breeding pairs that count in the objective function. This limit is determined by λ . See SI Table 16 for AR_s values for all 37 species.

2c. The 3rd approximating optimization problem

$$\max_{\hat{\mathbf{x}}} \sum_{s=1}^{37} y_{s_1} + y_{s_2} + y_{s_3} + y_{s_4} \quad (99)$$

subject to

$$y_{s_1} \le \sum_{j=1}^{8176} \frac{\sum_{z=1}^{8176} H_{s_1 z} A_z P_{\alpha_1 jz} \left(\sum_{i=1}^{14} \hat{X}_z^i C_{s_1 i}\right)}{AR_s} \qquad s_1 \in S_1\{\alpha_s = \alpha_1\} \quad (100)$$

$$y_{s_2} \le \sum_{j=1}^{8176} \frac{\sum_{z=1}^{8176} H_{s_2 z} A_z P_{\alpha_2 jz} \left(\sum_{i=1}^{14} \hat{X}_z^i C_{s_2 i}\right)}{AR_s} \qquad s_2 \in S_2\{\alpha_s = \alpha_2\} \quad (101)$$

$$y_{s_3} \le \sum_{j=1}^{8176} \frac{\sum_{z=1}^{8176} H_{s_3 z} A_z P_{\alpha_3 jz} \left(\sum_{i=1}^{14} \hat{X}_z^i C_{s_3 i}\right)}{AR_s} \qquad s_3 \in S_3\{\alpha_s = \alpha_3\} \quad (102)$$

$$y_{s_4} \le \sum_{j=1}^{8176} \frac{\sum_{z=1}^{8176} H_{s_4 z} A_z P_{\alpha_4 jz} \left(\sum_{i=1}^{14} \hat{X}_z^i C_{s_4 i}\right)}{AR_s} \qquad s_4 \in S_4\{\alpha_s = \alpha_4\} \quad (103)$$

$$y_{s_1} \le \lambda \quad (104)$$

$$y_{s_2} \le \lambda \quad (105)$$

$$y_{s_3} \le \lambda \quad (106)$$

$$y_{s_4} \le \lambda \quad (107)$$

$$\vdots$$

$$\vdots \quad (108)\text{-}(111)$$

where α_w indexes the four species dispersal classes, each species belongs to one and only one dispersal class set *w*, $P_{\alpha_w jz}$ is an element in the following matrix,

$$\mathbf{P}_{\alpha_w} = \begin{bmatrix} 1 & e^{-\alpha_w d_{1,2}} & \cdots & e^{-\alpha_w d_{1,10372}} \\ e^{-\alpha_w d_{1,2}} & 1 & \cdots & e^{-\alpha_w d_{2,10372}} \\ \vdots & \cdots & \ddots & \vdots \\ e^{-\alpha_w d_{10372,1}} & e^{-\alpha_w d_{10372,2}} & \cdots & 1 \end{bmatrix}, \quad (112)$$

$d_{j,k}$ is the Euclidean distance between parcels *k* and *j*, and constraints (108)-(111) are equivalent to constraints (95)-(98). Set S_1 contains all species that disperse an average of 800 meters; set S_2 contains all species that disperse an average of 3200 meters; set S_3 contains all species that disperse an average of 8000 meters; and set S_4 contains all species that disperse an average of 32000 meters. The greater $P_{\alpha_w jz}$ is, all else equal, the greater y_{α_w} can become. $P_{\alpha_w jz}$ is greater when habitat that s_w can use is spatially clumped rather than dispersed. Just as in approximating optimization model (90)-(98), y_s indicates the number of breeding pairs of species *s* that is supported on $\hat{\mathbf{X}}$. Again, to avoid solutions that increase the number of breeding pairs to a very high level for a few species and keep the breeding pair counts for other species very low, an upper limit is placed on the number of breeding pairs that count in the objective function. This limit is determined by λ_{s_w} for each *w*. See SI Table 17 for information on which species belong to which dispersal classes.

To make approximating optimization model (99)-(111) more tractable the breeding pair constraints (100)-(103) can be re-written,

$$\begin{aligned} y_{s_w} &\leq \sum_{j=1}^{8176} \frac{\sum_{z=1}^{8176} H_{s_w z} A_z P_{\alpha_w jz} \left(\sum_{i=1}^{14} \hat{X}_z^i C_{s_w i} \right)}{AR_s} \\ &\leq \frac{\sum_{z=1}^{8176} H_{s_w z} A_z \gamma_{\alpha_w z} \left(\sum_{i=1}^{14} \hat{X}_z^i C_{s_w i} \right)}{AR_s} \end{aligned} \qquad (113)$$

where $\gamma_{\alpha_w z} = \sum_{j=1}^{8176} P_{\alpha_w jz}$.

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