Wear and Wibbenmeyer *Carbon Balance and Management* (2024) 19:40
https://doi.org/10.1186/s13021-024-00287-9

Carbon Balance and Management

RESEARCH

Land-use change, no-net-loss policies, and effects on carbon dioxide removals

David N. Wear[1*] and Matthew Wibbenmeyer[1]

Abstract

Background Carbon dioxide removal from the atmosphere (CDR) is a critical component of strategies for restricting global warming to 1.5°C and is expected to come largely from the sequestration of carbon in vegetation. Because CDR rates have been declining in the United States, in part due to land use changes, policy proposals are focused on altering land uses, through afforestation, avoided deforestation, and no-net-loss strategies. Estimating policy effects requires a careful assessment of how land uses interact with forest conditions to determine future CDR.

Results We evaluate how alternative specifications of land use-forest condition interactions in the United States affect projections of CDR using a model that mirrors land sector net emission inventories generated by the US government (EPA). Without land use change, CDR declines from 0.826 GT/yr in 2017 to 0.596 GT/yr in 2062 (28%) due to forest aging and disturbances. For a land use scenario that extends recent rates of change, we compare CDR estimated based on net changes in land use (Net Change model) and estimates that separately account for the distinct CDR implications of forest losses and forest gains (Component Change model). The Net Change model, a common specification, underestimates the CDR losses of land use by about 56% when compared with the Component Change models. We also estimate per hectare CDR losses from deforestation and gains from afforestation and find that afforestation gains lag deforestation losses in every ecological province in the US.

Conclusions Net Change approaches substantially underestimate the impact of land use change on CDR and should be avoided. Component Change models highlight that avoided deforestation may provide up to twice the CDR benefits as increased afforestation—though preference for one policy over the other would require a cost assessment. The disparities in the CDR impacts of afforestation and deforestation indicate that no-net-loss policies could mitigate some CDR losses but would lead to overall declines in CDR for our 45-year time horizon. Over a much longer period afforestation could capture more of the losses from deforestation but at a timeframe inconsistent with most climate change policy efforts.

Keywords Carbon dioxide removals, Land-use change, Forest carbon, Natural climate solutions

*Correspondence:
David N. Wear
wear@rff.org
[1]Resources for the Future, 1616 P Street NW, Washington, DC 20036, USA

Background

Global emissions pathways that restrict global warming to 1.5°C [1] and the US Long-Term Strategy for reaching net zero emissions by 2050 [2] require unprecedented carbon dioxide removals (CDR) from the atmosphere in addition to substantial emissions reductions. The majority of historical and anticipated CDR comes from vegetation and soils, and especially in forests. However, levels of CDR have been declining because of a combination of changes in forest conditions and land uses [3–5]. Future levels of land-based CDR will be determined by a combination of policies, forest biology, and market-driven demands for land in various uses. Projections of policy effects need to account for land-use and forest changes and how these two dynamics interact.

This study evaluates how alternative specifications of land-use changes affect projections of land-based CDR in the United States while accounting for dynamic forest inventories. We developed a detailed projection model for land CDR that mirrors the historical inventories of CDR provided by the US government [5], using the same core data sets (plot-level data from USDA's National Resources Inventory, NRI, and the US Forest Service's Forest Inventory and Analysis, FIA) and the same aggregation logic. This model, which we call the Carbon and Land Use Model, or CALM, is based on comprehensive modeling of all land uses and the dynamics of forest carbon stocks, including harvesting and all other forest disturbance vectors. It allows us to make projections that are directly comparable to the historical inventories of CDR. We compare a model of net land-use changes with one that addresses all component changes, where all gains and losses are modeled. The net change model does not distinguish between changes in the carbon density of forest gains and forest losses so results in biased CDR estimates, especially when net change involves large offsetting gains and losses in forest area. Component change models account for these countervailing effects. We further explore alternative assumptions about the interaction of land-use changes with the structure of the forest inventory using the component change model.

Land-based CDR has been addressed using various formulations of land-use change. Integrated assessment models generally account for land-use changes but not forest dynamics that would support an explicit link between use decisions and forest carbon outcomes [6]. Forest land-use change is modeled either as net change or with a component change approach at high levels of aggregation and without links to forest dynamics, which amounts to a de facto net change model. Global forest sector models, such as the Global Timber Model [7] and the Global Forest Products Model [8], address forest dynamics using age-based yield curves and allow for endogenous change among rural uses with exogenous projections of urban uses, but because land use and carbon are specified at national levels, they cannot address subregional differences in carbon stocks. Similarly, FASOM-GHG, a partial equilibrium model of the US forest and agricultural sectors, uses exogenous projections of urban land use, downscaled to subregions based on historical patterns of change [9]. The resulting model approximates a component change approach at broad scales. Empirical models of land-use change [10, 11] have been used to evaluate CDR policies but without a link to the carbon content of existing forest land or forest dynamics. We developed a similar fine-scale empirical model of all component land-use changes linked to forest carbon inventories and dynamics. This allows us to test how various land-use change formulations affect CDR projections.

Most policies focused on enhancing CDR from land intend to affect emissions outcomes by changing land uses, including through tree-planting initiatives (afforestation) [12] and smart-growth initiatives that avoid deforestation [13]. Other mechanisms, not addressed in this paper, involve forest management treatments for enhancing carbon stocks, such as delaying timber harvests or expanding the utilization of wood in the built environment (e.g., through mass-timber products) that would grow the complementary carbon sink of harvested wood products. The literature on nature-based climate solutions emphasizes afforestation as the most effective tool for expanding CDR from land [14–16]. Motivated in part to protect forest climate benefits, some US states (Maryland, Connecticut, New Jersey) have proposed no-net-loss policies that use afforestation banks to offset deforestation. The 145 countries that have signed the Glasgow Declaration on Forests at the 26th UN Climate Change Conference of the Parties "commit to working collectively to halt and reverse forest loss and land degradation by 2030," though it is not clear whether the commitment defines forest loss as gross deforestation or would be based on a net change measure [17]. Nor is it clear whether change would be based on a use or cover measure [18]. The potential efficacy of these policies needs to be evaluated in a way that accounts for how land-use changes interact with existing forests and forest dynamics to determine changes in CDR.

The formulation of land use change also factors into country level commitments to reduce greenhouse gas emissions. National Greenhouse Gas Inventories (NGHGI's) based on IPCC good practice guidelines and accounting for component land use change, estimate country-level progress toward Paris Agreement goals, while Integrated Assessment Models (IAMs) are used to evaluate strategies for achieving these goals, including regionally aggregated land uses [19]. Grassi et al. [20] identify large discrepancies between NGHGI and IAM estimates of LULUCF net emissions due to differences in scope and land representations and provide adjustment factors for reconciling IAM projections with NGHGI monitoring data. Fuchs et al. [21] find that the use of net change within IAMs (as linked with Earth System Models) understate land use changes by up to 50%, and likely underestimate emissions. In this study we examine how alternative formulations of land use change affect estimates of net emissions from the LULUCF sector and provide a method for projecting net emissions at the country-level that is fully consistent with the structure of the U.S. NGHGI—i.e., it addresses component (gross) changes for all land use categories with explicit links to vegetation dynamics. Our model provides a means to link climate strategies and specific policies with their CDR outcomes consistent with monitoring data from the NGHGI and with detailed mechanisms of land use change.

Methods

With CALM, we model net carbon emissions from the land sector in the United States at the county level based on persistent land uses and land-use changes using a combination of net emissions factor and stock change approaches. Consistent with greenhouse gas (GHG) inventories, we categorize nonfederal land use based on broad categories from the NRI: cropland (Z), forest (F), settlement (S), and other (O, which includes rangeland, pasture, and participation in the Conservation Reserve Program). We treat land uses on federal lands as fixed and account for net emissions from federal forests. To estimate net emissions from nonforest land uses and changes between nonforest land uses, we apply time-constant net emissions factors (emissions minus sequestration per acre), calculated based on the US Environmental Protection Agency's Greenhouse Gas Inventory [5]. We account for net emissions from changes in forest conditions—including forest aging, disturbances, and management regimes in the forest land uses—and net emissions from conversions into and out of forest using a stock change approach based on plot-level data from US Forest Service FIA data (i.e., net emissions are defined by the difference in year-to-year carbon stock estimates). We model nonfederal land-use changes at the county level but model forest conditions and carbon outcomes for ecological regions defined by county aggregates to allow for the exchange of data between model components.

Net emissions from nonforest uses

For each time step, we define a 4×4 change matrix of nonfederal land-use categories for each county with diagonal elements defining persistent land-use area and off-diagonal elements defining all from-to changes. Define the land-use change matrix for county i at time t as

$$A_{it} = \begin{bmatrix} a_{it}^{Z,Z} & a_{it}^{Z,S} & a_{it}^{Z,O} & a_{it}^{Z,F} \\ a_{it}^{S,Z} & a_{it}^{S,S} & a_{it}^{S,O} & a_{it}^{S,F} \\ a_{it}^{O,Z} & a_{it}^{O,S} & a_{it}^{O,O} & a_{it}^{O,F} \\ a_{it}^{F,Z} & a_{it}^{F,S} & a_{it}^{F,O} & a_{it}^{F,F} \end{bmatrix} \quad (1)$$

where elements $a^{k,j}$ define area in use k at time *t*-1 and in use *j* at time *t*, including both federal and nonfederal lands, and units are acres. The difference between the vector of row sums and column sums defines net land-use change for the categories. The sum of all matrix elements is equal to the total nonfederal land area in a county.

Define the net emissions factor[1] for nonforest land uses and land-use changes as

$$c = \begin{bmatrix} c^{Z,Z} & c^{Z,S} & c^{Z,O} & 0 \\ c^{S,Z} & c^{S,S} & c^{S,O} & 0 \\ c^{O,Z} & c^{O,S} & c^{O,O} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (2)$$

where elements $c^{k,j}$ define net carbon emissions per acre for area in use *k* at time *t*-1 and in use *j* at time *t* (units are million metric ton CO_2 equivalents). Elements involving forest area or forest area changes are set to zero and are modeled using the stock change approach described below.

The net carbon emissions for nonforest land uses and land-use changes among nonforest land uses in county *i* is defined by the Hadamard product of A_{it} and c:

$$c_{it}^{NF} = A_{it} {}^{\circ} c \quad (3)$$

Summing elements of c_{it}^{NF} defines total nonforest net emissions, $\bar{c}_{it}^{NF}$, and summing across counties defines national totals:

$$\bar{c}_{t}^{NF} = \sum\nolimits_{i=1}^{N} c_{it}^{NF}. \quad (4)$$

Net emissions from forests

Area-based net emissions factors are inadequate for describing carbon sinks in forests because the rate of net emissions varies substantially with forest age, species composition, disturbances (including harvest), and characteristics of soils associated with forest location [22, 23]. As well, transitions into and out of forest uses involve an accounting for standing forest biomass and the transfer of soil carbon into or out of forest uses (the latter is necessitated because we use net emissions approaches

[1] We use lowercase c to refer to emissions or flows of carbon but uppercase *C* to refer to stocks of stored carbon.

for nonforest land and stock change approaches that include soil carbon for forest land).

We allow forest carbon stocks and net emissions to differ across several dimensions and define "forest classes," indexed by *m*, based on combinations of forest species group, stand management class, ownership, and region. Forest species groups, indexed by *q*, include softwood and hardwood species groups (Q=2). Stand management classes, indexed by *s*, include planted, nonplanted, or aggregated (*S* = *2 or 1*, depending on species group and region). Ownership classes, indexed by *v*, separate federal and nonfederal ownerships (V=2). Finally, regions, indexed by *r*, are Bailey's ecoregions at the province level (*R*=*20*). Altogether, forest species groups, stand management classes, ownerships, and regions define $M = Q \times S \times V \times R$ forest class.[2] For each forest class, in each time period, we define an $L \times 1$ vector (F_{mt}) with elements f_{lmt} describing the forest area in each age class within the forest class *m* (age groups are defined differently for eastern and western forests because of data availability). Each of these M vectors defines a "population" of forests to which we apply a separate population dynamics model.

Each forest area vector is aged using an $L \times L$ age transition matrix:

$$F_{m,t+1} = T_m \, F_{mt}. \tag{5}$$

T is defined as a Lefkovitch transition matrix that allows for disturbance-related mortality (including harvest) and aging transitions among age classes and imposes a maximum age limit on the forest population. We set the maximum age class based on the maximum age of forest observed in the FIA data—150 years for eastern regions and 210 years for western regions. The carbon stock at time t (C_{mt}^F) arrayed by forest age class is estimated by multiplying a $1 \times L$ vector of carbon density estimates (d_m, units are MT C/acre) by the transpose of the respective forest area vector:

$$C_{mt}^F = d_m F'_{mt}. \tag{6}$$

Net emissions are defined as the negative of between-period change in forest carbon stocks, where λ converts mass of solid carbon to atmospheric (CO_2) equivalents based on the ratio of their molecular weights (λ = 44.01/12.01).

$$c_{mt}^F = -\left(C_{mt}^F - C_{m,t-1}^F\right) \times \lambda \tag{7}$$

$$\bar{c}_t^F = \sum\nolimits_{m=1}^{M} c_{m,t}^F \tag{8}$$

This expresses the flow of carbon in a growing forest as a reduction in atmospheric carbon (negative values, consistent with nonforest emissions factors). Conversely, shrinking forest carbon stocks imply emissions to the atmosphere (positive values).

Total net land-based carbon emissions are defined as the sum of net emissions from nonforest land and forest land (Eqs. 4 and 8).

$$e_t = \bar{c}_t^{NF} + \bar{c}_t^F \tag{9}$$

Emissions from land-use changes involving forests

We now focus on how to incorporate forest land-use changes in the last row and last column of the change matrix in Eq. 1. Recall that a land-use change matrix is defined for each county and that forest carbon is modeled for areas defined by a combination of region, forest, management, and ownership types, organized by age classes. After assigning each county *i* to a region *r* based on its plurality of forest area, we define the area of forest gains (FG) and forest losses (FL) for each region as follows:

$$FG_{rt} = \sum\nolimits_{i \in r} \sum\nolimits_{k \in \{Z,O\}} a_{it}^{k,F} \tag{10}$$

$$FL_{rt} = \sum\nolimits_{i \in r} \sum\nolimits_{j \in \{Z,S,O\}} a_{it}^{F,j}. \tag{11}$$

We distribute forest gains and forest losses to forest classes within each region such that

$$FG_{rt} = \sum\nolimits_{m \in \mathcal{M}_r} fg_{1mt} \tag{12}$$

$$FL_{rt} = \sum\nolimits_{m \in \mathcal{M}_r} \sum\nolimits_{l=1}^{L} fg_{lmt}, \tag{13}$$

where fg and fl are the forest gains and losses, respectively, within age class or in forest class *m* and $\mathcal{M}_r$ is the set of forest classes within region *r*.[3] For forest gains, all new forest land is added to the youngest age class (l = 1). NRI data and land-use models do not assign area changes to the specific forest classes that are assigned based on FIA data. Therefore, we experiment with several approaches, described below, for allocating gains and losses. We then assemble age class–specific values of fg and fl into $L \times 1$ vectors FG_{mt} and FL_{mt}, respectively, and modify Eq. 5 to account for forest land-use changes:

[2] Because S is variable across regions and owners, the total number of groupings is 79.

[3] That is, the dimension of M_r is Q×S×V.

$$F_{m,t+1} = \boldsymbol{T}\, F_{mt} + FG_{mt} - FL_{mt}. \quad (5')$$

A final step in modeling total land-based net carbon emissions is to account for the transfer of soil carbon stocks associated with land-use changes between forest and nonforest uses. Estimates of forest carbon stocks (C^F in Eq. 6) include aboveground and belowground biomass as well as a substantial amount of soil carbon. When a unit of land moves from nonforest to forest uses at age 0, the forest carbon pool immediately increases by the stock of soil carbon. Because carbon emissions and not stocks are modeled on the nonforest land, the transfer of soil carbon from the nonforest use is not accounted for. As a result, failing to account for the transfer of soil carbon to forest would cause double counting. We correct for the double counting using soil carbon debits and credits. Define the soil carbon transfer (SCT) of forest-related land-use changes as

$$SCT_{mt} = (FL_{mt} - FG_{mt}) \times\ sc_m \quad (14)$$

where *sc* is the average soil carbon density for the referenced component of the forest inventory.

The accompanying soil carbon transfers are addressed by modifying Eq. 8 as follows:

$$\bar{c}_t^F = \sum_{m=1}^{M} c_{mt}^F + SCT_{mt} \quad (8')$$

With these adjustments to Eqs. 5 and 8, land-based net carbon emissions described by Eq. 9 account for net emissions for forest areas and changes (stock change model), for nonforest areas and changes (net emission factor model), and for carbon transfers between the two models.

Data and estimation

Land carbon sinks are not directly observed; therefore, we approximate components of net emissions described in the preceding section using a variety of models and data sources, including the national Greenhouse Gas Inventory (GHGI) [5], FIA [24], and NRI [25], which surveys land-use change on nonfederal lands.

We construct net carbon emissions estimates for the nonforest land-use categories of the NRI (crop, settlement, and other) based on the GHGI. These estimates provide our measures of the elements of c (Eq. 2). We construct these per acre emissions coefficients by dividing net emissions by area within individual nonforest land-use and land-use change categories reported in the GHGI, and we use national average values from 2015 to 2020. Conversions of land across uses (described in A_{it}) are tracked and modeled at the county level based on data from the NRI.

FIA plot records include assignment to an ecological province based on the National Hierarchical Framework of Ecological Units [26]. We assign each plot to its ecological province (our regions defined as an aggregate of sections) and assign each county to a province based on plurality of forest area in each province. After merging four small provinces with adjacent provinces, we have 20 provinces (Fig. 1). Provinces are based on commonality of various factors, including climate, geological features, potential vegetation, soils, and hydrology and therefore define a useful aggregation of plots for modeling carbon productivity [27].

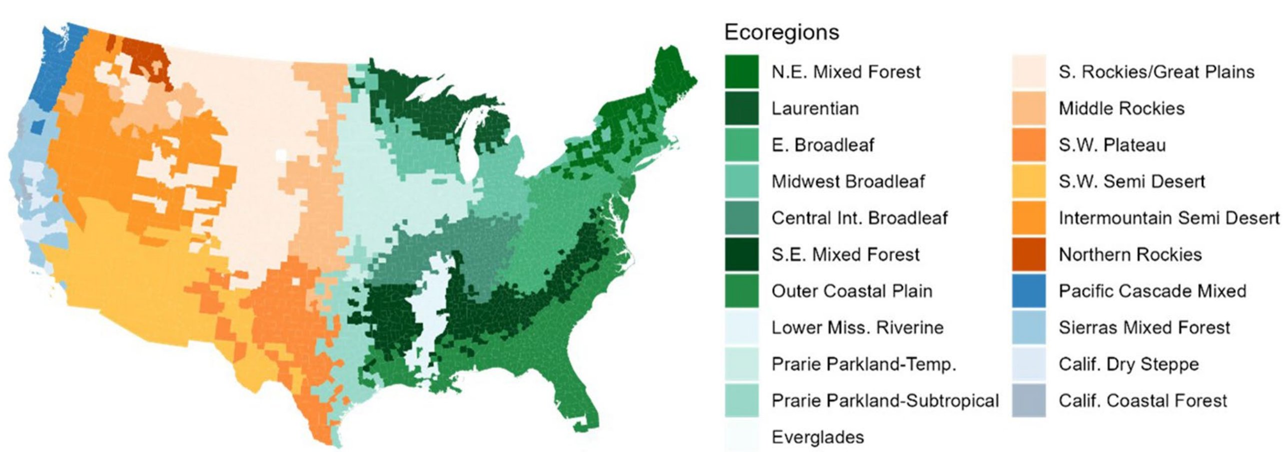

Fig. 1 US Ecological Provinces and Broad Regions. Each county is assigned to a province based on its forest area's most common type, as shown by the FIA database. Broad regions are defined by aggregates of the ecoregions: The Pacific Coast region is defined by the blue shaded ecoregions; the Southeastern region is defined as the combination of S.E. Mixed Forest, Outer Coastal Plain, Lower Mississippi Riverine, and Prairie Parkland -Subtropical; the Northeastern region is defined as all the green shaded ecoregions outside of the Southeast. The Arid West is defined by the orange to red shaded ecoregions

Net emissions from forests are derived from carbon stock change estimates of individual forest classes based on measured change in forest carbon observed in FIA data. We use FIA plot data to define the current distribution of forest attributes (F_m vectors), transition matrixes (T_m, Eq. 5), and the forest carbon stock density coefficients (d_m, Eq. 6).[4] FIA inventory records include estimates of forest carbon stock based on measured tree biomass and a set of ancillary variables for six carbon pools (live-tree biomass, downed dead wood, standing dead trees, understory vegetation, forest floor and litter, and soil organic carbon; see Woodall et al. 2015). We use the CARBON function in the R package rFIA [28] to query the FIA databases for the 48 conterminous states for plot estimates of per acre carbon stocks along with identifiers for age (which we convert to age class 1…*L*) and forest class (*m*). We sum component pools to define total carbon stock per acre for each plot. For each forest class, we use these plot records to fit an equation defining forest carbon density (t/hectare) as a function of forest age class.[5] Predicted values are used to define the d_m vectors. We specify carbon density models as logistic functions of measured forest carbon stocks and ages:

$$d_{m,i}(t) = K/(1 + e^{\alpha - \theta t_i}). \tag{15}$$

This assumes an asymptote or carbon-carrying capacity of K (t/hectare), which we define as 0.925 times the maximum observed carbon density in each forest class (*m*); this excludes some large outlier estimates from the modeling. Letting $\widetilde{d_{m,i}}(t) = d_{m,i}(t)/K$ define the proportion of carrying capacity observed at *t* allows for estimation of the logistic curve using ordinary least squares:

$$\ln\left(\frac{\left[1 - \widetilde{d_{m,i}}(t)\right]}{\widetilde{d_{m,i}}(t)}\right) = \alpha + \theta\, t_i + \epsilon \tag{16}$$

We use the estimated regression equation to define discrete elements of the carbon density array d_m for each forest class *m*. Using this regression approach rather than average observed densities addresses data missing for some age classes and high variability in older average densities linked to small samples. The predicted carbon density curves (Table S1) are summarized in Fig. 2. The highest density of carbon is found in mature forests in the Pacific Coast region. In the Southeast, despite lower densities, the rate of accumulation in young stands is high. Planted forests accumulate carbon more rapidly in early years than do naturally regenerated forests in the Pacific Coast and the Southeast.

We estimate transition matrices (T_m) using queries of measured change in remeasured plots using the AREACHANGE function of rFIA to define the area of forest moving between age classes for each of the forest classes defined above. Not all states in the Arid West have remeasured plots in the FIA database, but all ecological provinces have plots from which a transition matrix could be estimated. For each forest class *m*, we then sum transitions between age classes and derive periodic proportional changes.[6] Where initial age classes are missing from the queries, we apply the average transition probabilities from adjacent rows of the transition matrix. Forests do not age beyond the maximum age class *L*, but mortality shifts some of this area to younger ages. For eastern forests, where inventory remeasurement is more frequent, we use five-year age classes with a maximum age of 150 years; in the Pacific Coast and Arid West, we use 10-year time steps with a maximum age of 210 years. The resulting predicted age class distributions from estimated transition matrices (T_m) are summarized in Fig. 3 (see also Fig. S1). The age class distributions in Fig. 3 shift to the right over time, but the average age increases by less (9.5–16.9 years) than the time step (20 years), reflecting the effects of harvesting, disturbance, and tree mortality in plots with multiple age cohorts, consistent with previous studies [23].

Modeling scenarios

The focus of our analysis is on understanding how specification of land-use change vectors (Eqs. 10 and 11) affects estimates of CDR. We examine two alternative formulations of changes in forest land: one based on net changes in total forest land, and a second that addresses all components of net change and accounts for differences in the carbon content and dynamics of gains and losses of forests. Note that land-use models that provide component land-use changes but don't address differences in the forest carbon densities of losses and gains are equivalent to our net change formulation. In all cases, we assume that forest land use changes occur only on nonfederal lands. Model comparisons are based on a land-use projection

[4] In some cases, individual plots may span more than one forest stand, defining "condition" components of the plot. We use condition records to generate estimates. For ease of exposition, we refer here to "plot" records.

[5] Plot records indicate that many plots contain trees of variable ages. Forest age is defined by the average age of the dominant age class, and we assume that this age, when intersected with forest type and region, defines a characteristic forest condition. The average age of the dominant age class generally increases as a linear function of time, and empirical transition probabilities capture the aging process.

[6] The FIA sampling protocol calls for remeasuring fixed plots on a rotating basis and at an interval of five to 10 years. All eastern states, Plains states and Pacific Coast states have recorded remeasurements in their databases, but few remeasurements are available for Rocky Mountain states. We build models based on ecological provinces and can construct all age transition matrices from available data. Those for the Rocky Mountain states are based on few observations, relative to the total area, and may be less certain than for other regions.

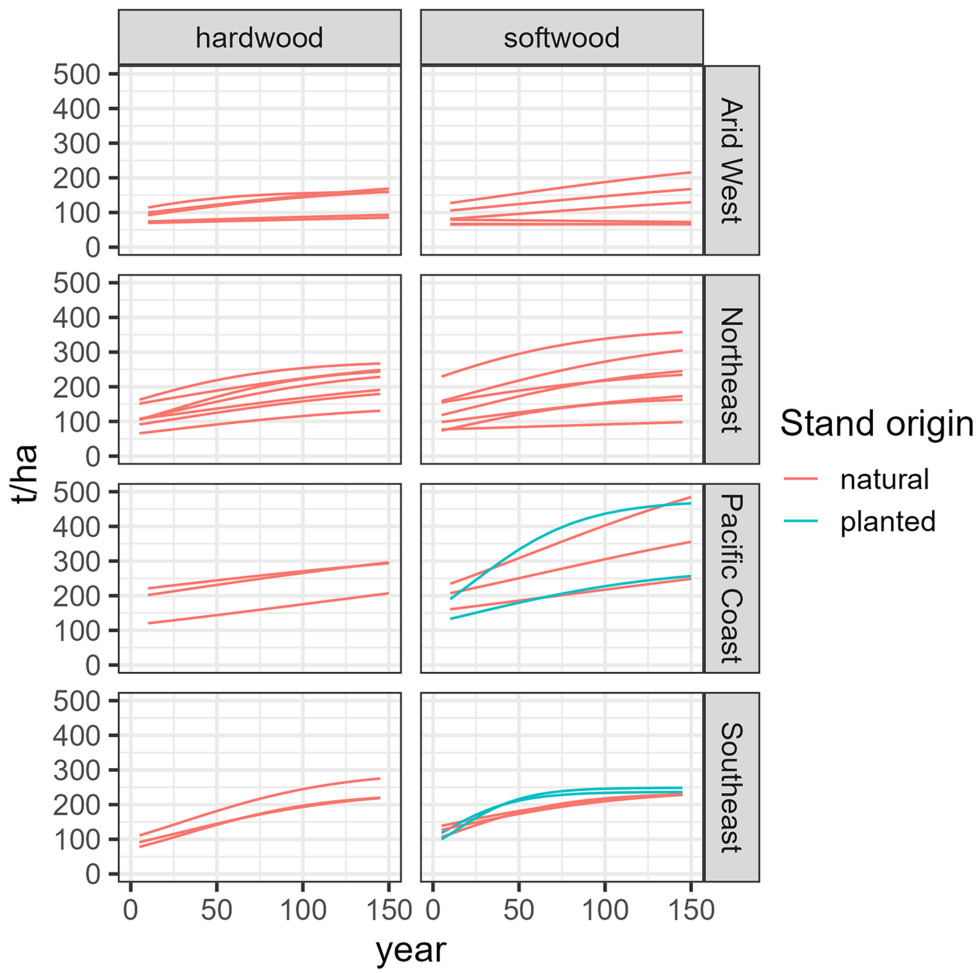

Fig. 2 Predicted Carbon Densities (tons/ha), by Forest Type and Region. Each line represents the relationship between density and age for ecological provinces and origin classes in each region and forest type grouping (see Eq. 16)

designed to extend recent patterns of land-use change over a 45-year period.

1. Net change model. This model assumes we have information only on net changes in total forest land, and thus defines net forest change for each region as $NC_r = FG_r - FL_r$, where *FG* are forest gains and *FL* are forest losses arrayed by age classes. We distribute NC_r to each forest class proportionally according to its share of nonfederal forest area in its region at *t*-1. A de facto net change model would also result when forest gains and losses are observed and modeled but without accounting for differences in their distribution across forest cohorts.
2. Component change models. These models make use of data on forest gains and losses, allowing us to compare net emissions estimates with those derived from data on net changes only. We independently link FG_{rt} and FL_{rt} to forest cohort components using two approaches. In the *base case*, gains enter as forests of age zero (age class 1) on nonfederal lands in proportion to the aerial extent of each forest class. Losses are applied across all age classes in proportion to the aerial extent of each forest class. In the *intensive case*, we adjust the base case by assuming that, in regions with extensive planted forests (the Southeast and parts of the Pacific Coast), new forests enter the model as planted forests.

Results

To evaluate the effects of land-use change specifications, we first simulate the effects of a scenario with no land-use changes. To allow for comparability with national GHGI for the land-use, land-use change, and forestry sector, we include CDR from wood product carbon pools, which we hold constant at the average rate observed between 2016 and 2020. For this scenario, projections reflect only the evolution of forest carbon stocks due to changing age class distributions within each forest class. These forest

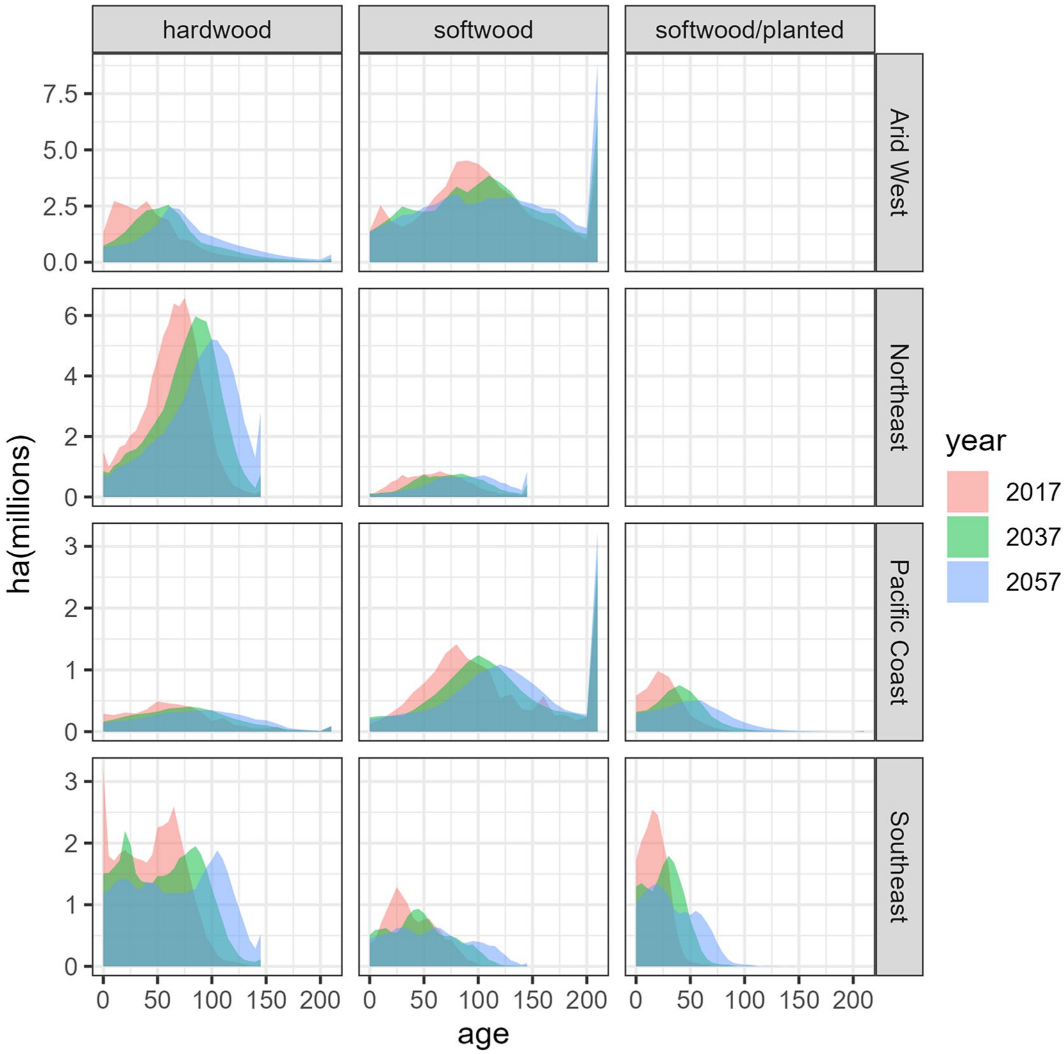

Fig. 3 Age Class Distributions, by Forest Type and Region, 2017, 2037, and 2057. The data are based on transition models for each ecological province, forest type, origin, and owner class, and the results are totaled

dynamics lead to a substantial reduction in the CDR rate for the land sector: it falls from 0.826 GT/year in 2017 to 0.596 GT/year in 2062. Changes in CDR are greatest in the hardwood regions of the Northeast and for planted pine forests in the Southeast (Fig. 4). These downward shifts are associated with forests that are aging out of their high carbon accumulation phases (to the right of the inflection point in carbon accumulation curves, shown in Fig. 2). The shift is especially acute in planted pine forests, where young trees grow very rapidly.

We then consider CDR under a projected land use change scenario. Projected land use change on non-federal US lands is based on NRI data and a discrete choice land use model similar to Lubowski et al. 2006. The model is parameterized based on land-use change trends from 1997 to 2012, and county-level estimates of land use returns over that period, as well as, in the case of urban land uses, population growth estimates. We then combine model estimates with land-use returns as of 2012 to project land-use change from 2012 to 2062.

Figure 5 maps and Fig. 6 summarize projected changes in four aggregate land-use categories—cropland, forest, settlements, and other—by the end of the simulation period (2062). Under this scenario, we project strong shifts out of cropland and into other land uses and settlements in the Upper Midwest; farther west, we project some expansions of cropland and shifts out of other land uses. Projections indicate declines in forest area throughout the period in the Southeast and Pacific Coast regions (Fig. 6 and Table S2). In the Northeast, forest area is projected to continue expanding until about 2035 and then decline for the remainder of the projection period. In the Northeast and the Southeast, net changes are the result of larger component changes (gains and losses); in the Pacific Coast, steady losses in forest area are not offset by gains. These projections do not take into

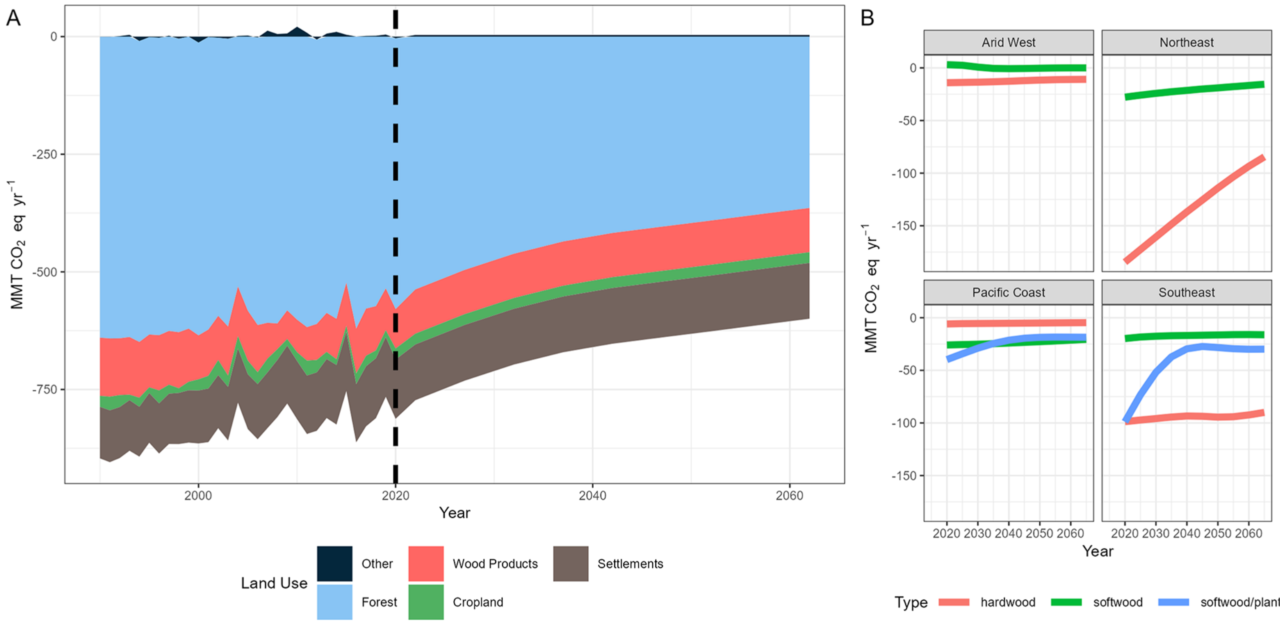

Fig. 4 Carbon Dioxide Removals. (**A**) Historical (1990–2020) and Projected (2022–2062) CDR, by Land Use. (**B**) Forest CDR with No Land-Use Change, 2022–2062, by Forest Type and Region

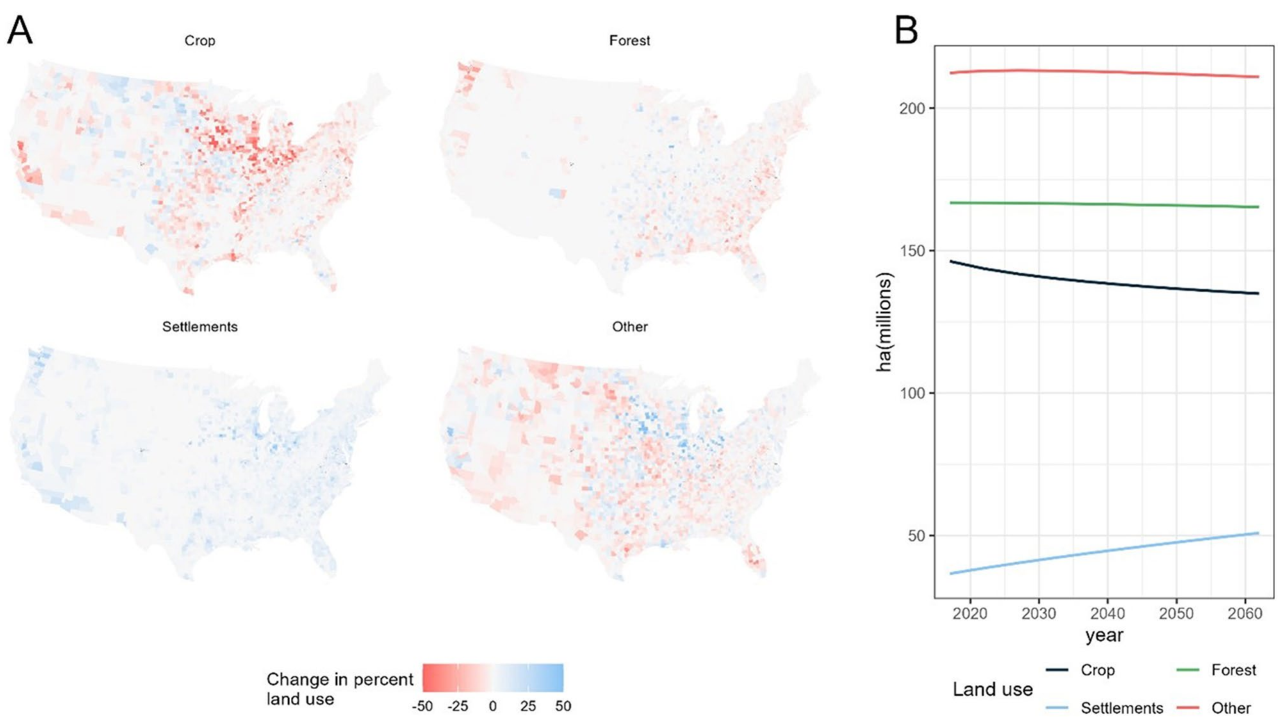

Fig. 5 Projected Changes in US Land Use, 2012–2062, by Type. (**A**) Percentage Change, by County. (**B**) Total Changes, in Million Hectares. In (**A**), all values greater than 50% are set equal to 50% for visualization

account several factors that could be important in driving land use change, including recent changes in migration dynamics due to the rise of remote work. However, our primary goal here is to test how projected forest CDR for a given land use change projection differ by model formulation, not to provide definitive projections of future US land use change.

The estimated effects of land-use changes on forest CDR vary substantially among model formulations (Fig. 7; Table 1). The net change formulation, based on assigning net change in forest area across all forest types

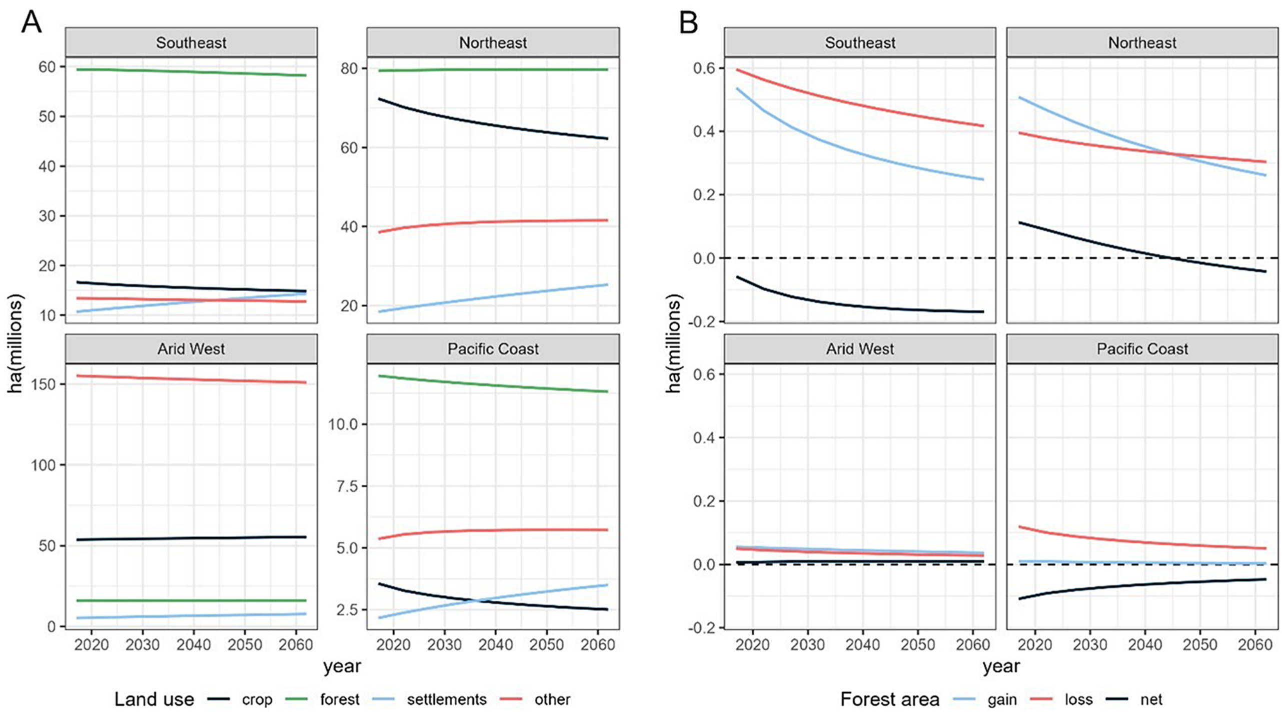

Fig. 6 Projected Changes in US Land Use and Forest Area, by Region, 2012–2062. (**A**) Crop, Forest, Settlement, and Other Uses. (**B**) Forest Gains, Losses, and Net Changes

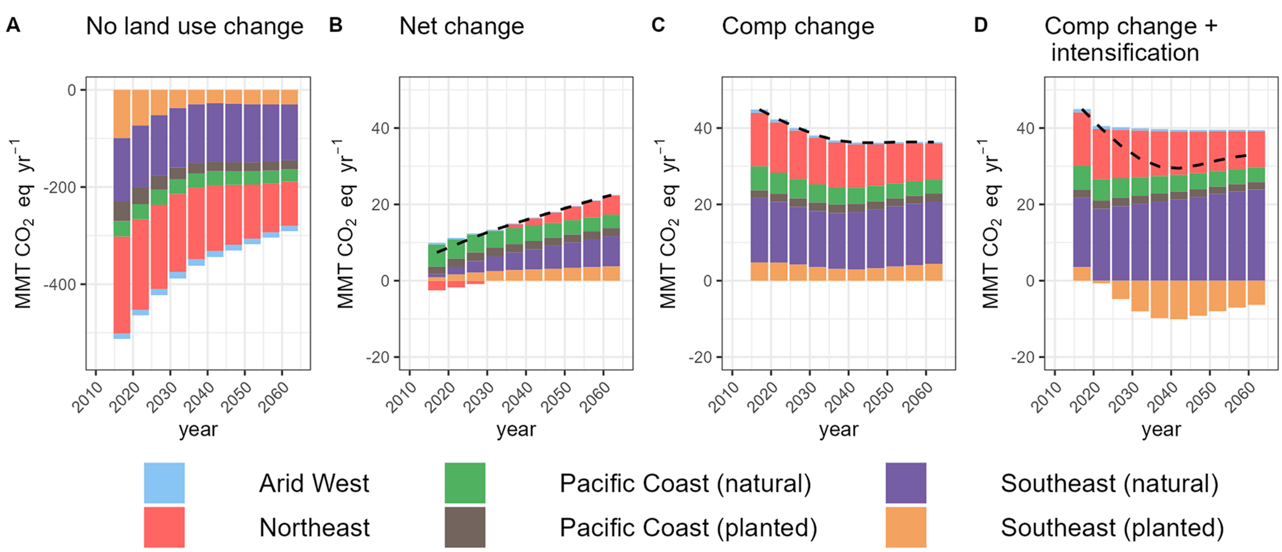

Fig. 7 Patterns of Forest Carbon Sequestration, by Region. (**A**) Base Case with No Land-Use Change. (**B**–**D**) Difference between Base Case and Alternative Land-Use Models. Bars for the Southeast and Pacific Coast regions differentiate forest origin class (planted or natural). Dashed lines show the total difference. Negative values indicate net sequestration of atmospheric carbon; positive values indicate net emissions

proportionally by area, further reduces estimated CDR by 772 MMT CO_2 over the simulation period, or by about 17.2 MMT CO_2/year. The component change model, which distinguishes between carbon implications of gains and losses to forest area, reduces estimated CDR by 1,894 MMT CO_2 over the simulation period, or by about 42.1 MMT CO_2/year. For the intensive case, where afforestation activities are focused on rapidly growing planted forests in the Southeast and the Pacific Coast regions, the reduction in CDR is mitigated somewhat: CDR falls by 1,673 MMT CO_2, or about 37.2 MMT CO_2/year.

The influence of the land-use change specification varies by region. The net change model underestimates CDR losses in regions where much land-use change is concentrated: by 61% in the Southeast and by 88% in the Northeast. In contrast, the net change model underestimates

Table 1 Change in net emissions (MMT CO_2 eq) under alternative land-use models, 2017–2062

Region	Land-use model results compared with base case		
	Net change	Component change	Component change + intensification
Arid West	12.6	23.1	23.1
Northeast	66.8	568.4	568.4
Pacific Coast (natural)	215.2	228.2	234.0
Pacific Coast (planted)	106.0	106.8	101.6
Southeast (natural)	237.9	773.2	1048.1
Southeast (planted)	133.4	194.3	-302.0
Total	771.8	1894.0	1673.3

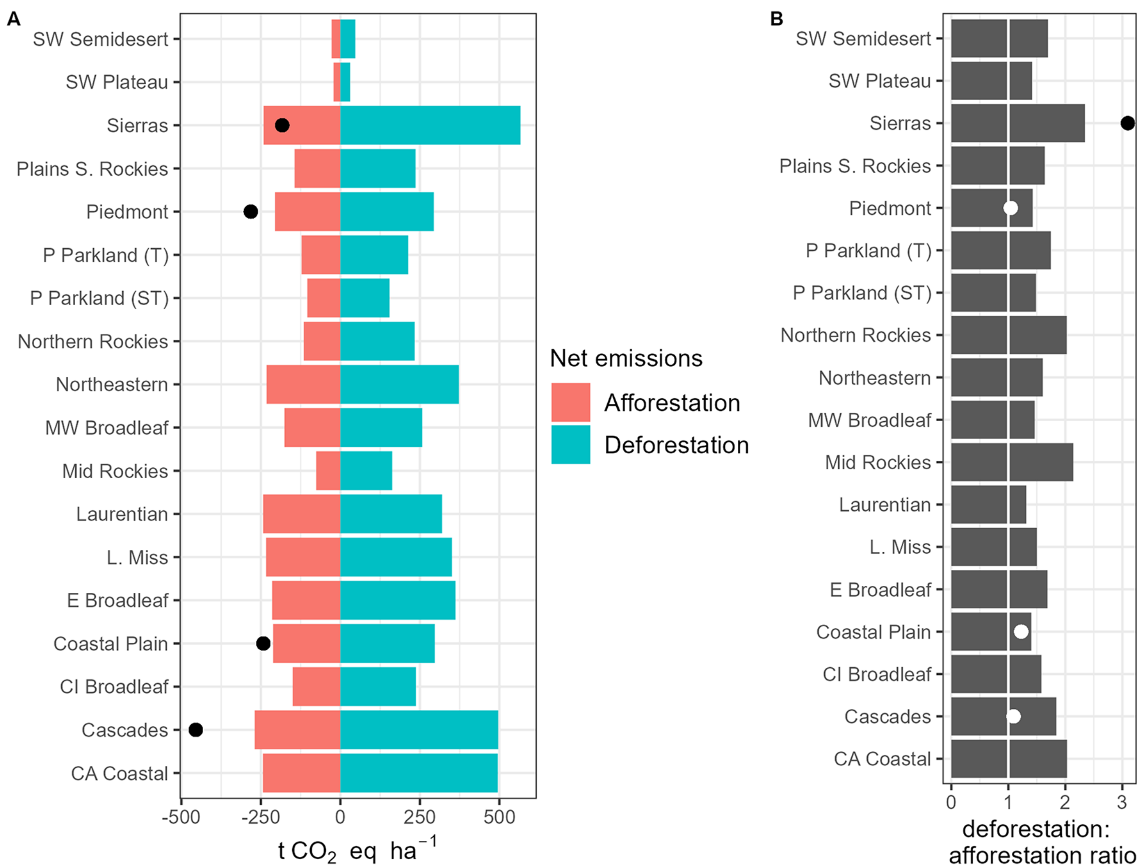

Fig. 8 Carbon Emissions in 2020, by Ecological Province. (**A**) Net Emissions Effect over 45 Years of 1 ha of Deforestation and 1 ha of Afforestation. (**B**) Ratio of Deforestation and Afforestation Emissions Rates. In (**A**), the points show the net emissions effects (t C / ha) of planted softwood forest afforestation in four provinces, and in (**B**), the points show the ratio of deforestation and afforestation emissions rates for these planted forests

CDR losses by about 4% in the Pacific, where most projected forest losses are not offset by forest gains.

At the national level, the net change model underpredicts CDR losses projected by the component change models by 54 to 59%, reflecting the disparity of carbon densities in afforested and deforested land as applied to our specific land-use change scenario. The effects for other scenarios would be different, depending especially on the regional distribution of land-use changes. That is, these effects vary across regions based on the existing distribution and maximum carbon densities of forests and on the growth responses of afforested lands.

To further explore the implications of variable afforestation and deforestation rates as described in the component change model, we conduct experimental runs with the CALM model. To simulate the effects of afforestation (deforestation), we model the CDR effects of adding (removing) a hectare of forest from (to) the other category in each ecological province at the beginning of the simulation period. We apply a weighted average of effects by forest types within each ecological province. The resulting changes in CDR reflect differential rates of forest carbon accumulation based on each region's modeled carbon productivity and the effects of all forest disturbances over the period. In all ecological provinces, the CDR gains from one ha of afforestation do not fully compensate for CDR losses from one ha of deforestation over the 45-year period. That is, 45 years is not long enough to recapture CDR losses from deforestation. The ratio of afforestation gains to deforestation losses (Fig. 8B) defines the number of ha required to compensate for CDR losses due to one ha of forest loss; it ranges from a low of about 1.4 ha in several northeastern and southeastern provinces, including the southeastern Coastal Plain and Piedmont, the Midwestern Broadleaf, and Laurentian provinces, to more than 2 ha in western regions, including the California Coastal, Cascades, Sierras, and Rocky Mountain provinces.

We apply the same approach to estimate the CDR gains accruing to planted forests alone. Planted softwood forests generally produce more CDR than the average forest condition during the 45-year simulation period (see the points in Fig. 8A). In the Cascades, Piedmont, and Coastal Plain ecological provinces—those with the most active forest management in the United States—the ratio of afforestation gains to deforestation losses approaches 1.0 (see the points in Fig. 8B). Here, CDR from afforestation with planted forests would nearly offset CDR losses from deforestation over the period.

Discussion

We developed a model that couples an empirical land-use choice model with a model of land-based carbon dynamics. CALM is specified such that we can evaluate the interaction of land-use changes with detailed forest conditions and dynamics as they affect changes in land-based CDR. Because the model incorporates both a complete description of forest inventories (including age, forest type, ownership, origin class, and ecological region) and a transition model that incorporates historical rates of disturbances (including wildfire, harvesting, insects, diseases, and wind events), projections of CDR fully account for growth potential and ongoing disturbance losses. As a result, our estimates of the effects of afforestation and deforestation on carbon dynamics account for expected losses due to these factors.

We use CALM to evaluate how alternative models of land-use change affect estimates of CDR outcomes. We find that a net change approach substantially underestimates the CDR losses from our land-use change scenario (by 54 to 59%) because of the differences in CDR losses associated with deforestation and CDR gains from afforestation. Misspecification has its greatest consequence where net changes are the result of large offsetting areas of afforestation and deforestation (e.g., the Southeast). In areas where deforestation is not offset by much afforestation, the effects are muted (e.g., the Pacific Coast).

Conclusion

CDR from land is a critical component of global and US climate change mitigation strategies. The US Long-Term Strategy [2] and the Fourth Biennial Report [29] anticipate that land will provide a substantial carbon sink, and the Long-Term Strategy emphasizes the potential role of afforestation in building that sink. Both reports highlight the uncertainty about projections defined by the complexity of interactions between land use and biological growth components. Our results confirm the importance and nuance of land-use changes as they interact with forest conditions in determining the land sector's CDR in the United States. They also highlight how this source of CDR is expected to decline because of forest aging and disturbances: CDR would fall by 28% over 45 years even without land-use changes.

Our results further highlight how land-use changes interact with forest carbon stock dynamics to determine overall CDR in the land sector. Our component change model allocates land-use changes to reflect the overall distribution of forest conditions in each forest class but relies on a set of assumptions. A next step in refining estimates of CDR would be empirical models that assign changes to forest types based on observed transitions from forest inventories. Precision might also be enhanced by modeling forest dynamics for even smaller subregions or forest type groupings. We also show that changes at the intensive margin can alter CDR outcomes consistent with Tian et al. [30]. However, our models do not address the potential wood product market response to enhancing timber supplies and subsequent expansion in wood product carbon sinks. This defines an emphasis for our future research. Future research could also address switching between forest management intensity classes within the structure of our land-use model and consistent with forest sector models. Another extension of this modeling approach would be to incorporate emissions from agricultural production into projections. Currently, our modeling accounts for carbon storage on cropland and changes in carbon storage when land is converted into or out of cropland, but not for emissions from production; we note that projected declines in cropland would result in a net reduction in the greenhouse gas emissions associated with production activities.

Net change approaches substantially underestimate the effects of land-use change on CDR and should be avoided if estimates of all component changes are available. As is the case for wetland banking, no-net-loss rules might lead to exchange of low functioning for high functioning lands and a net loss of ecological services. Although global forest sector models incorporate an approximation of component changes, integrated assessment models generally lack the details on current forest stocks and dynamics that would allow for linking land-use dynamics to component changes in forest carbon sinks, especially at ecologically meaningful scales [31]. This limits their ability to evaluate avoided deforestation as a policy instrument.

Component change approaches suggest that avoided deforestation may provide up to twice the CDR benefits as increased afforestation, though policy design would require further cost assessment. Our estimates derive from average productivity estimates, and the benefits of avoided deforestation would likely increase if focused on the most productive forest lands within a region. In the US, private forest policy has focused mainly on tree planting subsidies to encourage reforestation and afforestation. Both afforestation and forest retention are encouraged by expanding forest revenues, by growing demands for wood in various uses from bioenergy [30] to mass timber [32] that could grow carbon sinks in both forests and harvested wood products. No net loss policy proposals at the state level (e.g., New Jersey for public lands, Maryland, Connecticut) anticipate a mitigation banking or trading scheme. Our results highlight the need to base any such trades of forest losses for gains on changes in ecosystem service values–in this case the time path of CDR–consistent with a well-functioning environmental trading market [33]. Future research will include addressing the impacts of these policy instruments.

The disparities in the CDR effects of afforestation and deforestation indicate that while no-net-loss policies could mitigate some CDR losses, they would lead to overall declines in CDR for our 45-year time horizon. Over a much longer period, afforestation could offset more of the losses from deforestation but at a timeframe inconsistent with most climate change policy efforts. These results are also support concerns that efforts to curb deforestation, such as the Glasgow Declaration on Forests, would likely be ineffective at reducing global emissions, if based on a no-net-loss approach or using methods that linked component land use changes to average rates of CDR [17].

Abbreviations

CDR	Carbon dioxide removals
EPA	U.S. Environmental Protection Agency
GHGI	Greenhouse gas inventory
CALM	Climate and Land Use Model

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13021-024-00287-9.

Supplementary Material 1

Acknowledgements
Thanks to participants in the USDA Land Based Sinks Modeler Forum held September 22–23, 2022, in Atlanta for helpful discussions.

Author contributions
D.W. developed land and forest carbon dynamics models, collaborated on study design, wrote the initial draft of the manuscript, and contributed to editing and revisions.M.W. developed the land-use change models, collaborated on study design, and contributed to editing and revising the manuscript.

Funding
Alfred P. Sloan Foundation.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Competing interests
The authors declare no competing interests.

Received: 11 December 2023 / Accepted: 23 November 2024
Published online: 04 December 2024

References

1. IPCC. Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty [Internet]. 1st ed. Cambridge University Press. 2022 [cited 2023 Mar 23]. https://www.cambridge.org/core/product/identifier/9781009157940/type/book
2. US Department of State. The Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050. Washington, D.C. 2021 p. 61.
3. Wear D, Wibbenmeyer M. Prospects for Land Sector Carbon Dioxide removal in the United States. Report No.: 23–05: Resources for the Future; 2023. p. 20.
4. Smith S, Geden O, Nemet G, Gidden M, Lamb W, Powis C et al. State of Carbon Dioxide Removal – 1st Edition. 2023 Jan 29 [cited 2023 Apr 18]; https://osf.io/w3b4z/
5. U.S. Environmental Protection Agency. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2019. [Internet], Washington DC. EPA 430-R-21-005; 2021 [cited 2023 Feb 9]. https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-main-text.pdf
6. Daigneault A, Baker JS, Guo J, Lauri P, Favero A, Forsell N, et al. How the future of the global forest sink depends on timber demand, forest management, and carbon policies. Glob Environ Change. 2022;76:102582.
7. Sohngen B, Mendelsohn R, Sedjo R. Forest Management, Conservation, and global timber markets. Am J Agric Econ. 1999;81(1):1–13.
8. Buongiorno J, Zhu S, Zhang D, Turner J, Tomberlin D. The Global Forest products Model: structure, estimation, and applications. Elsevier; 2003. p. 320.
9. Wade CM, Baker JS, Jones JPH, Austin KG, Cai Y, de Hernandez AB, et al. Projecting the impact of socioeconomic and policy factors on Greenhouse Gas Emissions and Carbon Sequestration in U.S. Forestry and Agriculture. JFE. 2022;37(1):127–31.
10. Lubowski RN, Plantinga AJ, Stavins RN. Land-use change and carbon sinks: Econometric estimation of the carbon sequestration supply function. J Environ Econ Manag. 2006;51(2):135–52.
11. Lubowski R, Plantinga A, Stavins R. What drives land-use change in the United States? A National Analysis of Landowner decisions. Land Econ. 2008;84:529–50.
12. Domke GM, Oswalt SN, Walters BF, Morin RS. Tree planting has the potential to increase carbon sequestration capacity of forests in the United States. Proc Natl Acad Sci. 2020;117(40):24649–51.
13. Nelson AC. Smart Growth policies: an evaluation of programs and outcomes. J Am Plann Association. 2009;76(1):126–126.
14. Cook-Patton SC, Gopalakrishna T, Daigneault A, Leavitt SM, Platt J, Scull SM, et al. Lower cost and more feasible options to restore forest cover in the contiguous United States for climate mitigation. One Earth. 2020;3(6):739–52.
15. Fargione JE, Bassett S, Boucher T, Bridgham SD, Conant RT, Cook-Patton SC, et al. Natural climate solutions for the United States. Sci Adv. 2018;4(11):eaat1869.

16. Bastin JF, Finegold Y, Garcia C, Mollicone D, Rezende M, Routh D, et al. The global tree restoration potential. Science. 2019;365(6448):76–9.
17. Gasser T, Ciais P, Lewis SL. How the Glasgow Declaration on Forests can help keep alive the 1.5°C target. Proceedings of the National Academy of Sciences. 2022;119(23):e2200519119.
18. Grassi G, Conchedda G, Federici S, Abad Viñas R, Korosuo A, Melo J, et al. Carbon fluxes from land 2000–2020: bringing clarity to countries' reporting. Earth Syst Sci Data. 2022;14(10):4643–66.
19. Hasegawa T, Fujimori S, Ito A, Takahashi K, Masui T. Global land-use allocation model linked to an integrated assessment model. Sci Total Environ. 2017;580:787–96.
20. Grassi G, Stehfest E, Rogelj J, van Vuuren D, Cescatti A, House J, et al. Critical adjustment of land mitigation pathways for assessing countries' climate progress. Nat Clim Chang. 2021;11(5):425–34.
21. Fuchs R, Prestele R, Verburg PH. A global assessment of gross and net land change dynamics for current conditions and future scenarios. Earth Sys Dyn. 2018;9(2):441–58.
22. Wear DN, Coulston JW. From sink to source: Regional variation in U.S. forest carbon futures. Sci Rep. 2015;5(1):16518.
23. Wear DN, Coulston JW. Specifying forest sector models for forest carbon projections. J for Econ. 2019;34(1–2):73–97.
24. Bechtold WA, Patterson PL, Editors. The enhanced forest inventory and analysis program - national sampling design and estimation procedures. Gen Tech Rep SRS-80 Asheville, NC: US Department of Agriculture, Forest Service, Southern Research Station 85 p [Internet]. 2005 [cited 2023 Jul 20];080. https://www.fs.usda.gov/research/treesearch/20371
25. U.S. Department of Agriculture. Summary Report: 2017 National resources Inventory. Washington, DC: Natural Resources Conservation Service; 2020. p. 211.
26. Cleland DT, Freeouf JA, Keys JE, Nowacki GJ, Carpenter CA, McNab WH. Ecological Subregions: Sections and Subsections for the conterminous United States. General Technical Report WO-76D [Internet]. 2007 [cited 2023 Feb 22];76D. https://www.fs.usda.gov/research/treesearch/48672
27. McNab WH, Cleland DT, Freeouf JA, Jr.Keys JE, Nowacki GJ, Carpenter CA. Description of ecological subregions: sections of the conterminous United States. General Technical Report WO-76B. 2007;76B:1–82.
28. Stanke H, Finley AO, Weed AS, Walters BF, Domke GM. rFIA: an R package for estimation of forest attributes with the US Forest Inventory and Analysis database. Environ Model Softw. 2020;127:104664.
29. United States. United States of America. Biennial Reports (BR). BR3. BR4. National Communication (NC). NC 7. | UNFCCC [Internet], Washington DC. 2021 [cited 2023 Mar 31] p. 228. https://unfccc.int/documents/307954
30. Tian X, Sohngen B, Baker J, Ohrel S, Fawcett AA. Will U.S. forests continue to be a Carbon Sink? Land Econ. 2018;94:97–113.
31. Rose SK, Sohngen B. Global forest carbon sequestration and climate policy design. Environ Dev Econ. 2011;16(4):429–54.
32. Mishra A, Humpenöder F, Churkina G, Reyer CPO, Beier F, Bodirsky BL, et al. Land use change and carbon emissions of a transformation to timber cities. Nat Commun. 2022;13(1):4889.
33. Salzman JE, Ruhl JB. Currencies and the Commodification of Environmental Law [Internet]., Rochester NY. 2000 [cited 2024 Jun 17]. https://papers.ssrn.com/abstract=206628

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