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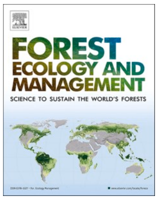

Middle-aged forests in the Eastern U.S. have significant climate mitigation potential

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ABSTRACT

Middle-aged forests in the Eastern U.S. are broadly defined to consist of forests between the regeneration phase following harvest or disturbance, and an older phase with forests composed of large trees, complex structure, and increasing natural mortality. Study objectives were to develop new carbon accumulation curves based on recent inventory data that represent the actual growth rates of forests as they advance beyond middle age; quantify the projected carbon sink from reducing or increasing harvest of middle-aged forests; and disseminate credible estimates of future carbon stocks in ecosystems and harvested wood products to support policies designed to enhance the role of forests in removing carbon dioxide from the atmosphere and storing it securely. We found that middle-aged Eastern U.S. forests could continue to accumulate carbon for many decades or several centuries in the absence of harvesting, with relatively low risk of natural disturbances. Compared with a recent study that estimated a potential increase in biomass of only 22%, and some analyses that anticipate significant increases in risks from natural disturbances, our results indicate a potential increase of about 100% over current biomass stocks by 2100. Temperate Continental forests have greater potential to increase carbon stock over longer time periods than Subtropical Humid forests. Results from scenario analyses showed that in the near term of 20–40 years, reducing harvest will yield the greatest reduction in net greenhouse gas emissions compared with business as usual. Under an extreme “no-harvest” scenario, C sequestration could increase by about 20 TgC yr^{-1} in Temperate Continental forests by 2050, and by about 30 TgC yr^{-1} in Subtropical Humid forests over the same time period. In contrast, a scenario of tripling harvest would increase C emissions by 30 and 60 TgC yr^{-1} in the Temperate Continental and Subtropical Humid ecozones by 2050, respectively. In the longer term of 80 or so years, all scenarios and “business as usual” converge toward similar impacts on greenhouse gas emissions, nearing neutrality in the Subtropical Humid ecozone but separated by about 30 TgC yr^{-1} in the Temperate Continental ecozone. Our estimated annual emission reduction from stopping harvest over the 73 million ha of middle-aged forests amounts to 117 Mg CO_2 per year in 2050, equivalent to about 7% of the emissions from using fossil energy in the two ecozones. Increasing harvest would have the opposite effect of increasing emissions by a similar magnitude in 2050. How middle-aged forests in the Eastern U.S. are managed can clearly affect their contribution to achieving net-zero GHG emissions by 2050 and beyond.

1. Introduction: Why focus on middle-aged forests?

Middle-aged forests are broadly defined to consist of forests between the regeneration phase following harvest or disturbance, and an older phase with forests composed of large trees, complex structure, and increasing natural mortality. Middle-aged forests may also be considered “mature” although this term has multiple definitions (Birdsey et al. 2023). In the Eastern U.S., middle-aged forests constitute approximately 75% of the forest area, with ages ranging from roughly 20 to 100 years after disturbance except in areas that experience high rates of harvesting and regeneration (Pan et al. 2011). Eastern middle-aged forests are heterogeneous, composed of natural or planted stand origins following conversion from agricultural use or disturbances from harvesting or natural events such as wildfire or insect outbreaks (Masek et al. 2011, Williams et al. 2016). Past management practices are also quite varied, ranging from intensive plantation regimes to periodic partial timber removal to preservation (Birdsey and Lewis, 2003). Generally, southern forests of the Eastern U.S. are more intensively managed for wood products, have more plantations, and are younger; whereas, northern forests of the Eastern U.S. tend to be managed less intensively with partial harvests, and are older and uneven-aged.

Management options and practices are highly varied in the Eastern U.S., but have significant consequences for carbon (C) stocks and climate over time (e.g. Nunery and Keeton, 2010; Zhou et al., 2013). “Working forests” have a history of management to yield a sustainable flow of industrial wood products, whereas nonindustrial forests typically have a history of partial cutting (or high grading) that occasionally yields industrial wood products but often lack a management plan that produces a steady flow of timber from well-stocked stands of trees (Butler et al. 2016). There is a large area of private forest land that is highly degraded and poorly stocked, which could benefit from restoration activities to restock the land with healthy trees (Hoover and Heath 2011).

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Eastern forests remove a significant quantity of carbon dioxide (CO_2) from the atmosphere each year and store it in the forest ecosystem and in harvested wood (Domke et al. 2021). Given the broad national interest in deploying “natural climate solutions” (NCS) to help reduce greenhouse gases in the atmosphere, increasing (or at least maintaining) this important function of forests is typically considered to be one of the main NCS approaches involving the land base (Fargione et al. 2018; National Academy of Sciences 2018). More specifically according to these studies, the greatest absolute potential among different forest-related activities in the temperate zone are improving forest management followed by increasing forest area and avoiding loss of forests. However, improving forest management involves some vastly different approaches and is subject to vigorous policy debate about whether additional timber harvesting or letting forests grow to old ages would be more effective at reducing GHGs. Middle-aged forests, if left to grow and absent natural disturbances, can become old growth while continuing to sequester C for many decades or centuries, and their old-growth status is highly valued for many reasons including protection of stored C (Keeton 2018; Moomaw et al. 2019). On the other hand, these same forests could be targeted for increasing harvest to respond to increasing demand for industrial wood products or biofuel. According to some studies, old-growth forests would provide more climate benefits if converted to intensive management for wood products by removing more CO_2 from the atmosphere than if they were left unharvested (Malmsheimer et al., 2011).

These different perspectives leave questions about whether old-growth forests in the Eastern U.S. could continue to remove more CO_2 from the atmosphere than they emit, since measurements of them are sparse given the rarity of these ecosystems. Ecological theories and some recent studies conclude that old forests become “carbon neutral” or even lose stored C because of declining productivity and increasing mortality (Odum 1969). Yet other research indicates that old forests and large trees often continue to sequester C at high rates. For example, observations of undisturbed old-growth forests suggest that C stocks continue to increase until and beyond the onset of old growth, a period of time that is typically hundreds of years for “intact” forests (Curtis and Gough 2018; Keeton 2018). In many areas of the East, stand-replacing disturbances are quite rare, indicating a low risk of future loss of C stock (Fraver et al. 2009), though it is possible that climate change will accelerate the frequency and intensity of natural disturbances (Ontl et al. 2020). An important consideration is that the timing and magnitude of reductions in C sequestration vary significantly among different forest ecosystems that do not experience stand-replacing disturbances, which is possibly due to characteristics and impacts of small-scale disturbance regimes (Curtis and Gough 2018).

A paper by Zhu et al. (2019) concluded that in the U.S. “the future (2080 s) biomass will only sequester at most 22% more C than the current level.” This estimate of potential appears low compared with some other studies (e.g. Curtis and Gough 2018; Keeton 2018), possibly because of sparse data about older forests and failure to consider the whole ecosystem C budget. That analysis did not account for age-related increases in detrital and soil C, which are important components of C sequestration in older forests. Most of the biomass stock estimates by forest type in Zhu et al. (2019) as well as “standard” reference data about C accumulation based on forest inventory data (e.g. Smith et al. 2006) reach or approach a maximum or an asymptote at about 100 years of age. However, intensive studies of older forests indicate that live biomass continues to accumulate for centuries. A compilation of global literature by Luyssaert et al. (2008) concluded that old-growth forests continue to sequester C, and that about half of the accumulation is in the live biomass with the remainder in detritus and soil. Examples from Eastern U.S. old-growth forests are consistent with this global analysis – for example as noted earlier, ecosystem C stock continues to increase as trees grow to large sizes and forest structure becomes increasingly multi-layered (Curtis and Gough 2018).

Studies that significantly underestimate the future potential forest C sink by older forests should not be used to inform mitigation policies in the forest sector. There is a high risk that mitigation policies which ignore the potential benefits of older forests could lead to excessive harvesting of middle-aged and old forests without having any climate mitigation benefit, and could even lead to additional emissions of CO_2.

The goal of this study is to take a broad look at middle-aged Eastern U.S. forests and assess their mitigation potential over time, focusing on the impacts on C stocks of several scenarios: increasing harvest of middle-aged forests, decreasing harvest, or maintaining a “business as usual” level of harvest through the end of this century. Of particular interest is the magnitude of the forest C sink in the year 2050, which is a relatively near-term target for climate action that depends in part on a significant contribution from forests (Bastin et al. 2019), and the year 2100 which represents a longer-term look at changes in C stocks of forests as they grow old or become more intensively managed. Specific objectives are: (1) develop new C accumulation curves based on recent inventory data that represent the actual growth rates of forests as they advance beyond middle age; (2) quantify the projected C sink from reducing or increasing harvest of middle-aged forests; and (3) disseminate credible estimates of future C stocks to support policies designed to enhance the role of forests in removing CO_2 from the atmosphere.

2. Approach and methods

2.1. Study areas

This study examines the potential of forests to accumulate additional C stocks in two large ecozones of the Eastern U.S.: Temperate Continental and Subtropical Humid (Fig. 1). The Temperate Continental ecozone encompasses most of the forest area in the northeastern quarter of the conterminous U.S., except for mountain areas above roughly 1,000 m elevation. The area of middle-aged forest represented in the scenario modeling is 33 million ha. The Subtropical Humid ecozone encompasses most of the forest area in the southeastern quarter of the U. S., excluding mountain areas above approximately 1,000 m, and the more tropical southern tip of Florida. The area of middle-aged forest represented in the scenario modeling is 40 million hectares.

For this study, middle-aged forests are defined as those forests having an age range from approximately 20–100 years. Although not all forests are even-aged, the U.S. Forest Service’s forest inventory (FIA) database assigns an age to most sample plots based on the plurality of stocking by trees of different ages. Age-class distributions from FIA for the two ecozones show that most forests in the Eastern U.S. are in the 20 to 100 year age classes (Fig. 2). The oldest forests sampled by FIA in the Temperate Continental ecozone are around 200 years old although most forests are less than 140 years old. There is a significant peak of data in the 45 to 85 year age classes. In the Subtropical Humid ecozone, most forests are less than 120 years old, and there is a significant area in the youngest age classes, 5 to 25 years old.

There is significant diversity of species composition in the two ecozones. Fig. 3 shows the percentage of area by main forest types. Oak-hickory (*Quercus and Carya* spp.) and maple-beech-birch (*Acer, Fagus, and Betula* spp.) are most common in the Temperate Continental ecozone, while oak-hickory (*Quercus and Carya* spp.) and loblolly-shortleaf pine (*Pinus taeda and Pinus echinata*) are most common in the Subtropical Humid ecozone.

2.2. Accounting standards

System boundaries include accounting for three main C stocks or fluxes associated with the forest sector: change in C stocks in forest ecosystems; change in C stocks in harvested wood products; and increases or decreases in CO_2 emissions from substitution of harvested wood for other materials (or vice-versa) within the study boundaries for scenarios that increase or decrease harvest volume compared with business as usual (BAU). Effects outside of these boundaries such as

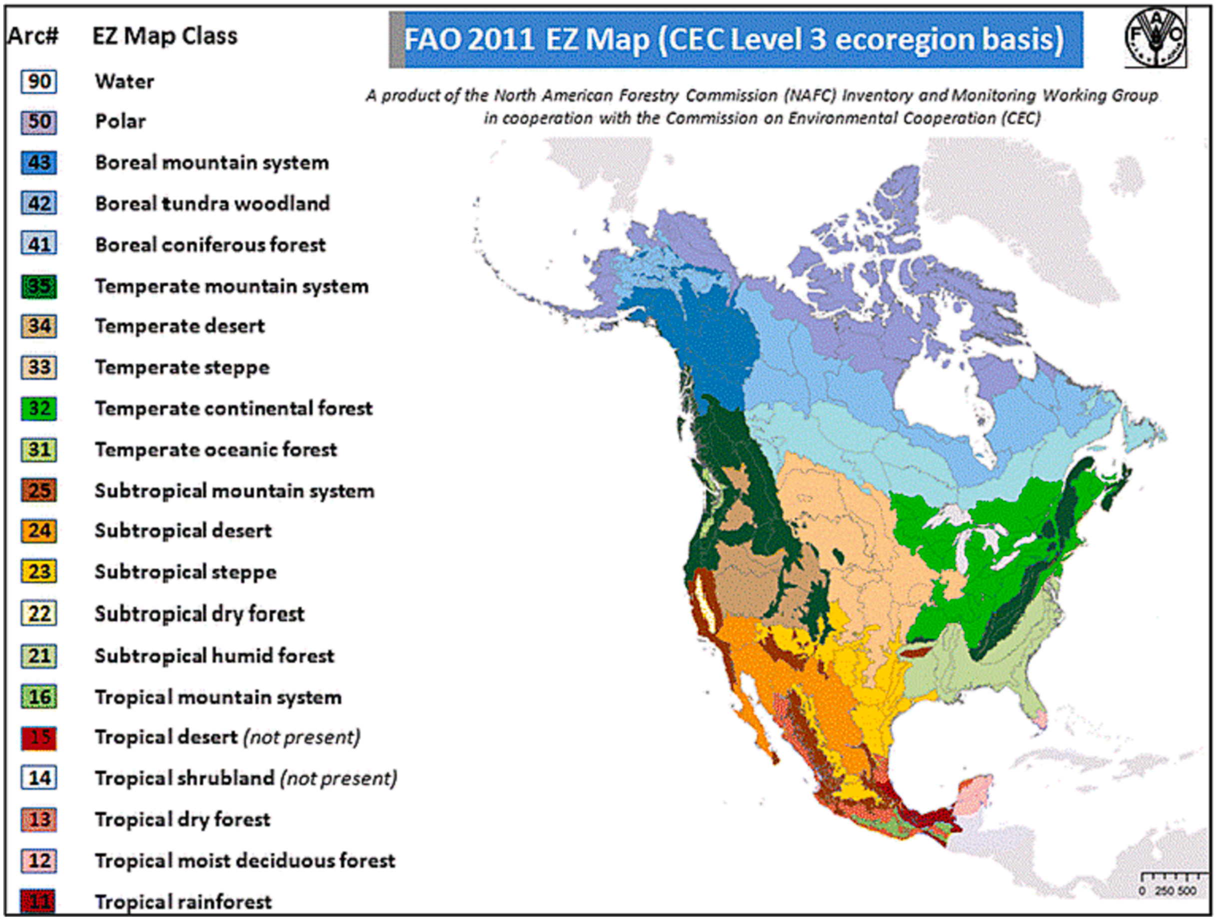


Fig. 1. Locations of the Temperate Continental ecozone (bright green) and the Subtropical Humid ecozone (light green). The FAO 2011 Ecozone map for North America has its basis in the Commission for Environmental Cooperation's level 3 ecoregions (Smith et al. 2018).

leakage or induced land-use change are not assessed because of significant uncertainties in data and methods for doing so. All of the main C pools in ecosystems are included in the C accumulation curves and the scenarios: live trees and understory vegetation, above- and below-ground; standing- and down-dead trees and debris; organic soil layers (or litter); and soils. However, only live above-ground biomass is used to estimate the asymptote representing an assumed neutral C flux (see description of C accumulation model). These pools are defined in accordance with FIA standards (Smith et al. 2006). Carbon stocks in harvested wood products include long-lived products and pulpwood remaining in use or disposed in landfills, also defined according to FIA standards. Substitution effects include changes in net emissions from using wood instead of other materials like steel and concrete, using wood instead of fossil fuel for energy, or using other materials or fossil fuel instead of wood.

Projections involve comparing scenarios with a projected BAU baseline so that the calculated changes in C stocks and emissions are "additional", i.e. calculated as the difference between the scenario and the BAU baseline. Risk of reversal in the future from natural disturbance is not quantified, though addressed at some length in the discussion. Other sources of uncertainty that are not quantified are also discussed, such as insufficient data on changes in soil C, and the uncertainty from using published generic displacement factors, i.e. the amount of avoided C emissions compared with the amount of C sequestered in the ecosystem and wood products, rather than calculating specific displacement factors for the study area.

2.3. *Forest inventory data for estimating carbon accumulation curves*

The approach to deriving C accumulation data by age class and ecozone is based on methods reported in Smith et al. (2006) except that more recent and comprehensive data from the FIA database were queried to construct new accumulation curves. Estimates of C stocks and stock-change in biomass of live and dead trees are based on direct and repeated inventory measurements; whereas for the non-biomass C pools, modeled estimates based on a subsample of FIA plots are used to populate the FIA database. The modeled estimates are very similar to those reported in Smith et al. (2006), as updated for compiling the current national FIA database (Domke et al. 2012; Woodall et al. 2011, 2015).

Changes in C stocks were estimated for "undisturbed forest remaining forest" which refers to forest land that has not been affected by land-use change (either reforestation or deforestation) or by disturbances including fire, insects, weather, and harvesting, following the standard approach developed by Smith et al. (2006). We chose to focus on undisturbed forests because our scenarios involved comparing the effects of different harvest levels on C stocks, excluding other disturbances and land-use change. Undisturbed forests may include an inherent level of tree mortality that is typically observed in forests as they grow older and self-thinning occurs, and there may also be lingering effects of past disturbances on growth especially in regions where recovery from disturbance is a slow process. Carbon accumulation curves represent all ecosystem C pools, except that currently available FIA data about soil C does not vary by age class, so does not contribute to age-related trends.

Changes in C stocks follow typical patterns after stand-replacing disturbances or reforestation. Figure S1 illustrates the pattern for

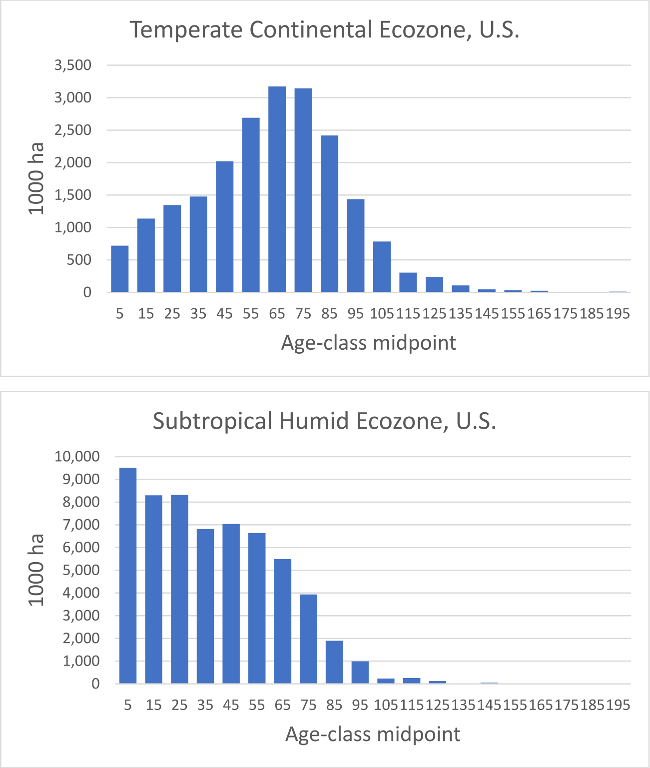


Fig. 2. Age-class distributions of forests in the two ecozones.

regeneration following fire. As shown, this pattern varies over time in predictable ways, but with significant spatial and temporal variability that is largely driven by disturbance history, age, forest type, and site. Because ecozones are comprised of many different forest types and resulting changes in C stocks represent averages of these variables, some supporting analyses were done for specific forest types within ecozones to help assess the implications of broad management scenarios for applications in more spatially resolved contexts.

Changes in C stocks were estimated by querying the FIA database using EVALIDator (U.S. Forest Service, 2023). FIA measurement protocol defines disturbances as affecting at least one acre and at least part of the inventory sample area. To remove the effects of recent disturbance from the data, sample plots were excluded if harvesting or disturbance were recorded in the field during the most recent remeasurement cycle. Past disturbances (those occurring prior to the most recent remeasurement cycle) were excluded by filtering those plots that had stocking less than 60% of “normal” as determined by FIA for each region and forest type. Plots that had stocking greater than 120% were also removed since these “overstocked” stands represent unusual conditions of high-density tree populations that do not represent typical fully stocked growing conditions. In the South, where forests are more intensively managed than other regions and where understocked forests quickly become fully stocked, the less than 60% stocking filter was not included.

All states had at least one complete remeasurement cycle of 5 to 10 years available in the database. The most recent complete inventory cycle from the database was selected. For biomass, the database variables included estimates of average annual change in either biomass or C, above- and below-ground, by age class, on a per-hectare basis. This enabled the use of a remeasurement approach to estimate C accumulation rates. All variables were converted to consistent units of megagrams per hectare per year (Mg/ha yr^{-1}). Data was retrieved in 10-year age-class groups for each ecozone. For other C pools, data was not available as an annual change but as C stocks per hectare for different age classes, so a stock-difference approach was used. To estimate average annual change, the difference in the estimated stock at two times divided by the number of years was calculated and converted to Mg/ha yr^{-1}.

Sampling errors for the estimates are generally quite low because of the large number of sample plots that contribute to each estimate at the ecozone scale. Sampling errors do not account for modeling errors, which can be quite large. Sampling errors were used in estimating the 95% confidence intervals that are described in the next section on C accumulation models.

2.4. *Carbon accumulation models*

The Chapman-Richards function that is commonly used in forestry applications was used to develop C accumulation curves for live trees from the FIA sampling data (Pienaar and Turnbull 1973):

$$y(t) = a\left(1 - e^{-bt}\right)^{p}$$

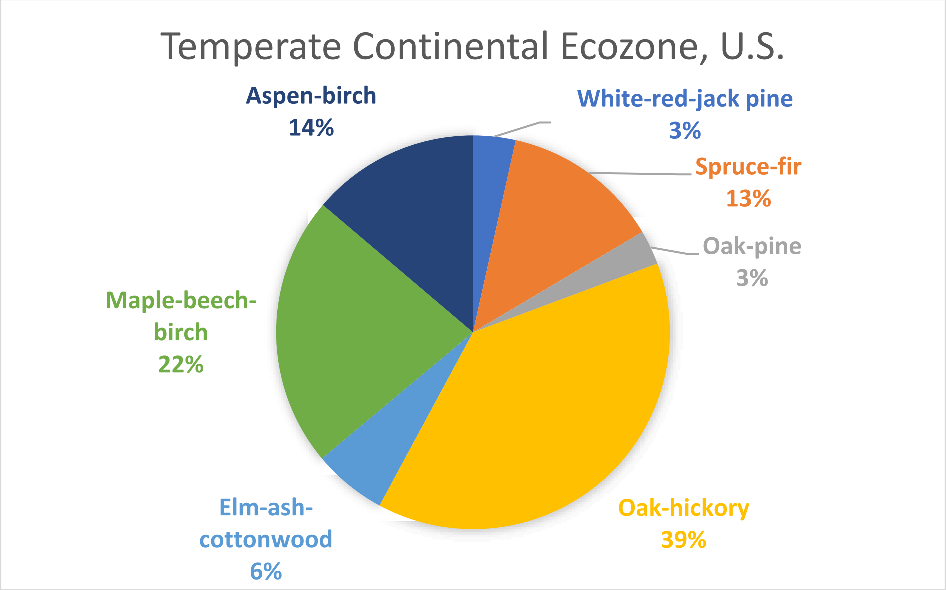
Where y is the C stock at time t, a is the asymptote, b controls the rate of approach to the asymptote, and p is a growth modifier that reduces the maximum growth rate to its state at time t. The “R” statistical package was used to estimate the parameters. The 95% confidence limits were based on sampling errors by age class as reported in the FIA database.

We used the calculated asymptote to represent the average maximum C stock, which assumes that on average, old-growth forests reach an equilibrium rate of zero with respect to net accumulation of C as represented by live-tree C. This is a common assumption in literature about old-growth, though measured rates of C accumulation by specific forest ecosystems do not uniformly indicate that C stocks in older stands are either increasing, decreasing or stable (Curtis et al. 2018; Keeton 2018; Lichstein et al. 2009; Luyssaert et al. 2008; Xu et al. 2014). Relatively few studies include changes in soil C – one study indicates that C accumulates in at least some old-growth soils (Zhou et al. 2006).

2.5. *Bookkeeping model*

The bookkeeping model used in this study was adapted from that used to estimate C fluxes from global and regional land-use, land-use change and forestry (LULUCF) for the Global Carbon Project (Houghton and Nassikas 2017; Houghton and Castanho 2023). The approach for estimating annual sources and sinks of C from LULUCF combines two types of data: rates of land use and land cover change, and C densities (Mg/ha). The bookkeeping model accounts for all of the C initially held in areas affected by LULUCF, simulating changes in four pools (living aboveground and belowground biomass; dead biomass, including coarse woody debris (slash); harvested wood products; and soil organic C). In the model, losses of C to the atmosphere occur both rapidly (fire) and slowly (decay), and recovering forests withdraw C from the atmosphere and accumulate it again in biomass and soil (Fig. 4). The model tracks the land areas and pools of C directly affected by human activity until they reach a new equilibrium in C density. The model follows cohorts, or age classes, of land. Rates of forest growth and rates of decay vary with type of ecosystem, type of land use, and region, but not through time. That is, rates are the same in 1850 as in 2020. The effects of environmental change (e.g., the concentration of CO_2 in the atmosphere, changes in climate, and N deposition) are not explicitly included in the bookkeeping model; however, the data used to estimate rates of growth and decay reflect the influence of all recent management and environmental factors combined. Rates of forest growth may be underestimated in the most recent years if those rates are now greater than one or two decades ago.

For this study, the bookkeeping model was parameterized separately for two ecozones of the Eastern U.S.: Temperate Continental and Subtropical Humid. The model was run from 1700 to the present using historical data on areas of LULUCF (Houghton and Nassikas, 2017) coupled with new estimates of C density by age class from this study.



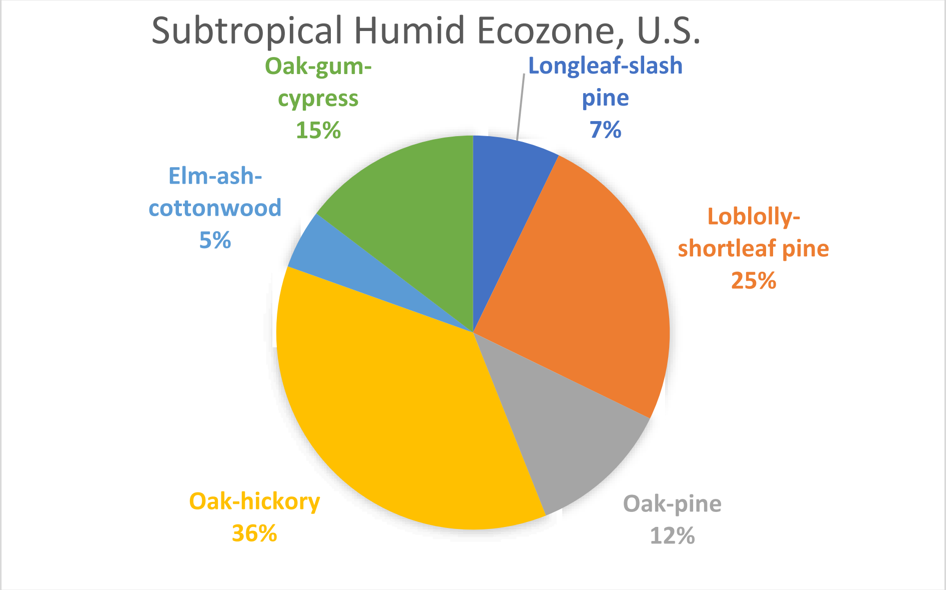


Fig. 3. Percent of forest area by main forest types for the two ecozones. See the main text for scientific names of the most common tree species groups.

Current estimates of area by age class in the model were compared with similar data from the FIA database and found to be comparable in age-class distributions although the total forest areas for the two ecozones were somewhat different because of area boundary inconsistencies. It was decided to use the areas in the model for the simulations rather than adjust them since the objective is to compare future scenarios with baselines for broad ecozones and not necessarily to represent scenarios for more specific geographic areas.

Harvest volume is a key driver for the bookkeeping model. Historical data from forest inventories is used to estimate harvest volume which is then converted to biomass in the model. In the U.S., some trees are harvested exclusively for bioenergy or for other industrial products, and some are harvested for multiple products. Harvests are assumed to be either clearcut or partial cut, and for either timber or fuelwood uses. Since our calculations are based on volume harvested per hectare and not per tree, harvesting of individual trees for multiple or single uses is not a factor in the simulations. For modeling of future harvest scenarios, the bookkeeping model follows a series of rules that target specific forest area cohorts for harvest and regeneration:

- Forests of the Subtropical Humid ecozone are assumed to be clearcut. After harvest, the age is reset to zero.
- Forests of the Temperate Continental ecozone are assumed to be selectively cut, and their age is reset to a lower age on the growth curve according to the amount of biomass that is harvested.
- Secondary forests are given priority for harvest over primary forests. However, primary forests will be harvested if there are insufficient secondary forests available.
- Minimum forest ages for harvesting fuelwood are 30 years for the Subtropical Humid ecozone and 50 years for the Temperate Continental ecozone.
- Minimum forest ages for harvesting industrial wood are 50 years for the Subtropical Humid ecozone and 95 years for the Temperate Continental ecozone.

Harvested and unharvested areas are allowed to grow and accumulate C according to their age as depicted by the C accumulation curves.

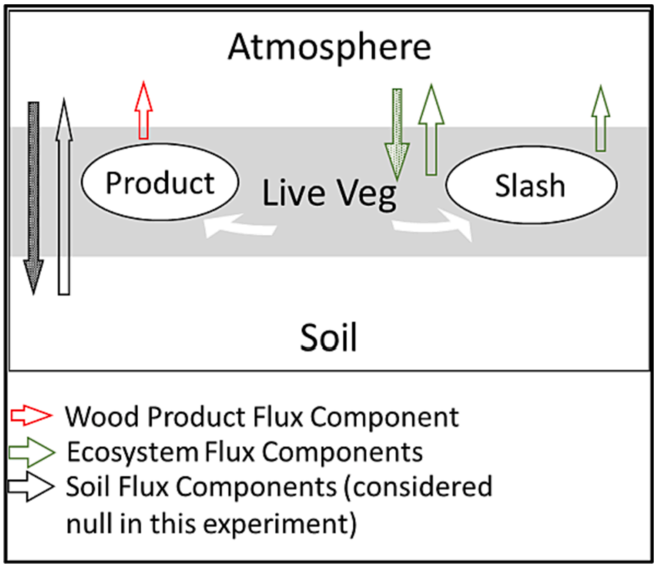


Fig. 4. Carbon fluxes represented in the bookkeeping model. For future scenarios in this study, areas of forest were held constant so flux components associated with land-use change are not shown.

2.6. Old-growth estimates

We reviewed literature for estimates of C stocks in remnant old-growth forests. Most of the available data was found within the Temperate Continental Ecozone. We selected data from forests at least 200 years old and showing no evidence of disturbance, as documented in the studies (Brown et al. 1997, Burrascano et al. 2013, Fisk et al. 2002, Gunn et al. 2014, Hoover et al. 2012, Lichstein et al. 2009, McGarvey et al. 2015). Almost all of the selected old-growth estimates were on sites dominated by hardwood species. All selected data sources included live above-ground C estimates; in some cases we added region-specific estimates for below-ground live C and the other C pools based on appropriately-matched FIA data. The old-growth data was only used to compare with the C accumulation curves derived from FIA data, and were not used in developing the C accumulation curves themselves. The old- growth data collection standards were reasonably comparable to FIA data, and at least some of the selected old-growth sites used identical measurement and calculation protocols.

2.7. Future scenarios

Because recent data indicated a stable forest land base with loss of forest area approximately equal to gain in area, and our objective was to focus on different timber harvesting levels, all future scenarios assume no changes in forest area. Future scenarios also assume that the C accumulation curves and natural disturbance rates are stable over the projection period. Then a BAU scenario was defined along with 4 alternate scenarios representing different levels of harvest of sawtimber and fuelwood. The BAU scenario represents a continuation of the past 5-year average harvest levels based on "FAOstats" data (Food and Agriculture Organization 2021), with forests allowed to re-grow after harvest according to the newly-derived C accumulation curves. Scenario 1 is a "no harvest" scenario that eliminated all harvesting of forests but left other variables the same as BAU. Scenario 2 is defined as one-half of the BAU harvest level; scenario 3 is 1.5 times BAU harvest, and scenario 4 is 3 times BAU harvest. The four harvest-change scenarios were compared with the BAU scenario to determine the additional C that would be stored or lost as a result of these actions. Although these scenarios are not intended to represent specific policy targets, they are designed to illustrate clearly the impact of different harvest levels on future C stocks.

The new harvest levels represented by the alternate scenarios were ramped up or down from BAU over 12 years to allow for a smooth transition from average historical levels of harvest (Figure S2). The bookkeeping model was used to project changes in C stocks over time until the year 2100.

2.8. Estimated substitution benefits

For increases in harvest volume we used a simple model based on published C displacement factors (Sathre 2010; Smyth et al. 2016) as reported in Dugan et al. (2018): 0.54 Mg displaced per Mg of saw and veneer logs, and 0.89 Mg displaced per Mg of biofuel. These factors were converted to negative values in scenarios where harvest was decreased. We did not consider future changes in use of fossil fuels and emissions in producing materials because of uncertainty in how the displacement factors might change over time (Harmon et al. 2019).

3. Results

3.1. Accumulation of live-tree carbon stocks

The resulting forest C accumulation curves and their confidence limits for the two ecozones are shown in Fig. 5. Data for both ecozones indicate a gradual slowing of C accumulation with age. Compared with the Temperate Continental ecozone, the rate of accumulation is greater

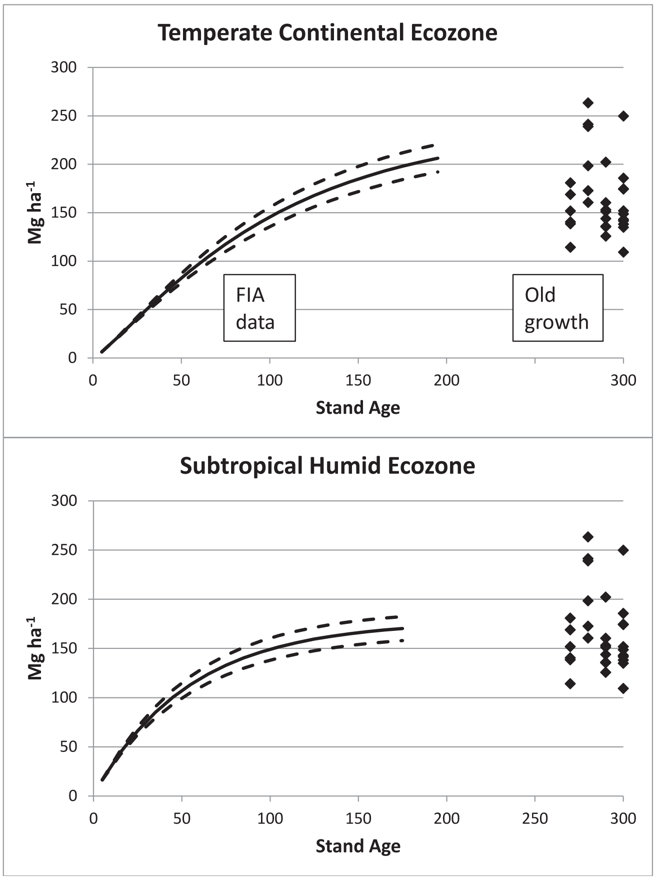


Fig. 5. Cumulative carbon stock in live-tree biomass by stand-age class for two ecozones, predicted by the Chapman-Richards equation. Dashed lines represent the 95% confidence interval of the estimates. Predictions for older age classes not shown because the underlying data is too sparse. Old-growth values from the literature (not used in constructing the C accumulation curves) are also shown to the right for comparison – most of the old-growth data are from the Temperate Continental ecozone, but are identically shown in the two graphs. Supplementary figure S3 shows comparable estimates for all non-soil C components.

in younger forests of the Subtropical Humid ecozone, but the accumulation of C saturates at a younger age.

As illustrated in Fig. 5, the parameterized equations estimate asymptotes of 241 MgC ha^{-1} for the temperate continental ecozone and 177 MgC ha^{-1} for the subtropical humid ecozone, with both occurring at ages greater than 200 years.

There is significant variability in the asymptote for different forest types within ecozones as shown in Table 1 for a few examples, which also include two forest types from the Western U.S. for comparison, Douglas-fir (*Pseudotsuga menziesii*) and Ponderosa pine (*Pinus ponderosa*). Oak-hickory (*Quercus and Carya* spp.) in the Central States had the greatest asymptote in the East, while Spruce-fir (*Picea and Abies* spp.) in the Northeast had the lowest.

The carbon accumulation models represent the average conditions over large areas that contain diverse forest types and growth conditions, such that these models will not necessarily represent the rate of C accumulation at smaller scales or for specific domains within the larger regions. For example, the curve for the spruce-fir (*Picea and Abies* spp.) forest type is different than the average for the Temperate Continental ecozone, and within the spruce-fir forest type, there are two distinct populations of trees for mesic and hydric sites (figure S4).

3.2. Non-soil ecosystem carbon stocks and accumulation

Accounting for C in forest floor and dead wood components increases the estimated total C stock significantly for both ecozones (Table 2). Data at the maximum age with sufficient sample plots to be representative (about 20–40), shows that the oldest forests in the Temperate Continental ecozone have significantly more C in all C components than the Subtropical Humid ecozone, commensurate with the 30-year difference in maximum ages.

The average annual change in C stocks for all ecosystem components except soil on undisturbed areas is shown in Fig. 6. Changes by age class follow a typical pattern of reaching a maximum growth rate at a young age, followed by a gradual decline over the subsequent years. The data indicate that the Subtropical Humid ecozone has a higher peak at a younger age, but that the difference between ecozones is less pronounced for middle-age classes. Higher average productivity in the younger ages results in faster C accumulation in the early years of the simulations for the Subtropical Humid ecozone. The estimates are highly variable for the oldest age classes because of fewer sample plots and also a naturally higher variability that is somehow rooted in the varied forest life histories and site qualities.

Table 2

Total non-soil C stock at maximum observed age, by component, based on available FIA data.

Ecosystem component	Temperate Continental ecozone Forest age = 155		Subtropical Humid ecozone Forest age = 125	
	(Mg/ha)	SE (%)[2]	(Mg/ha)	SE (%)[2]
Live biomass[1]	193.3	20.7	178.8	38.1
Standing dead trees	6.9	6.6	4.2	6.9
Down dead wood	12.0	6.3	7.9	5.8
Forest floor	33.5	10.4	11.1	3.0
Total non-soil ecosystem C	245.7	24.9	202.4	39.3

[1] Above-and below-ground, trees plus understory.

[2] Represents standard error of above-ground biomass only. Multiply by 1.96 for 95% CI.

3.3. Past and projected carbon balance under different scenarios

Modeled historical harvest data and impacts indicates that forests and wood products of both ecozones were approximately C neutral from 2000 to 2020 (Fig. 7), excluding changes in undisturbed forests. In the Subtropical Humid ecozone, the C fluxes of different scenarios diverge significantly through 2040 while BAU stays nearly neutral, but then all scenarios converge toward zero by 2100. For the Temperate Continental ecozone, the C fluxes of different scenarios diverge significantly through 2060 while BAU stays nearly neutral, and then scenarios begin to converge toward zero but at later decades than for the Subtropical Humid Ecozone. For both ecozones, a tripling of harvest results in a significant source of C throughout the projection period, while no harvest maintains a significant sink. BAU and the other harvest scenarios are bracketed by these two extremes.

Fig. 8 shows estimates representing all middle-aged forests whether harvested or not. Additional accounting for the impacts of substituting wood for other construction materials or fossil fuel from changing

Table 1

Estimated maximum live-tree carbon, for selected eastern and western U.S. forest types and the two ecozones analyzed in this study. Lower and upper bounds represent 95% confidence interval. Note that undisturbed sample plots were used to estimate the C stock at asymptote using an accumulation-of-growth approach, whereas all sample plots except those involving land-use change were used to estimate current median age and C stock. The potential additional C stock is the difference between maximum potential C stock at asymptote and current C stock at the median age. Scientific names for tree species are in the main text.

Forest type or Ecozone	Maximum Potential C Stock				Current and Additional C Stock		
	C stock at Asymptote	Lower bound	Upper bound	Age at asymptote	Current median age[1]	C stock at median age	Potential additional C stock
	Mg/ha			Years	Years	Mg/ha	
Northeast spruce-fir	192.0	179.2	204.8	280	105	62.4	129.6
Northeast maple-beech-birch	218.3	204.8	231.9	260	100	100.8	117.5
Lake States spruce-fir	215.5	200.4	230.6	400	120	44.9	170.6
Lake States maple-beech-birch	212.4	198.6	226.1	290	105	86.0	126.4
Central States oak-hickory	345.1	320.2	370.1	310	110	113.8	231.3
South loblolly-shortleaf pine[2]	245.3	229.0	261.5	160	60	105.1	140.2
Temperate Continental ecozone	240.6	225.4	255.9	320	105	89.4	151.2
Subtropical Humid ecozone	177.4	165.5	189.4	125	85	92.7	84.7
Western Douglas fir[3]	535.2	499.8	570.1	310	125	305.9	229.3
Western ponderosa pine[4]	221.9	207.1	236.7	175	125	130.5	91.4

[1] Age at which half of live-tree C is below and half is above.

[2] Excluding planted stand origins.

[3] Pacific Northwest, west side of the Cascades.

[4] Pacific Northwest.

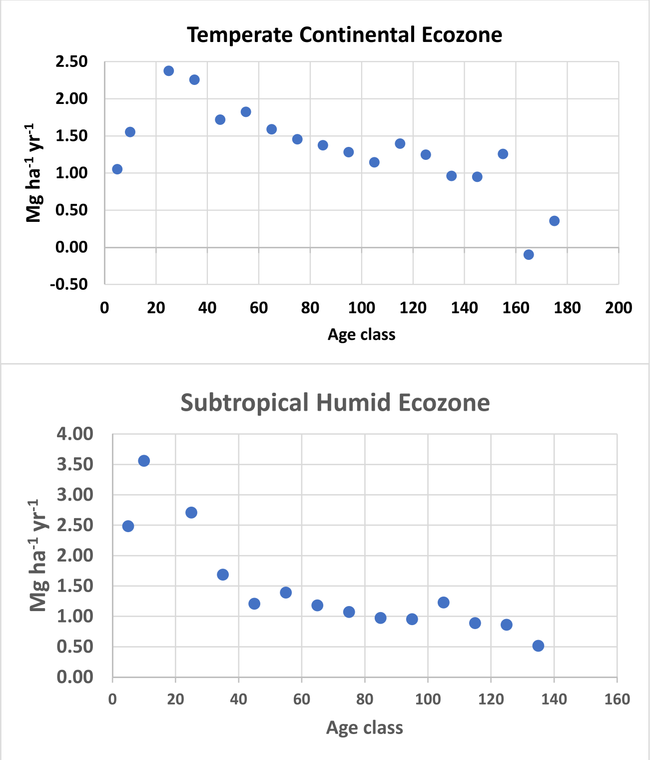


Fig. 6. Average annual change in C stocks, calculated as the difference between time periods divided by the number of years. Estimates are based on undisturbed sample plots.

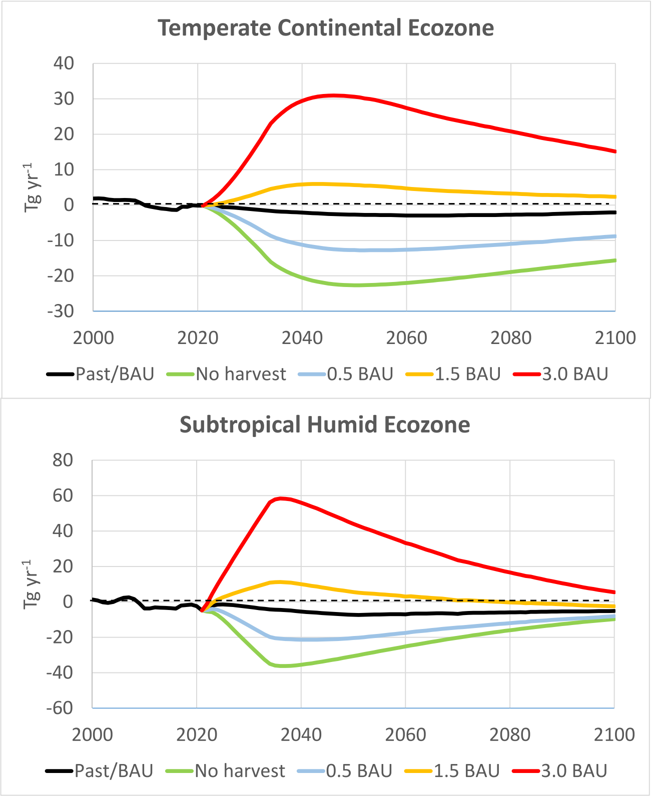


Fig. 7. Past and projected carbon flux under business as usual and several harvest scenarios (no harvest; 50% of BAU harvest (0.5 BAU); 150% of BAU harvest (1.5 BAU); 300% of BAU harvest (3.0 BAU). Values greater than 0 signify a C source, and values less than 0 signify a C sink. Data represent the sum of C fluxes in the forest ecosystem and harvested wood products associated with areas harvested (excluding undisturbed forest).

harvest levels reduces the magnitude of the differences between scenarios but does not significantly affect the results or the general trends (Fig. 8 and supplemental tables S1 and S2). The estimates clearly show that for both ecozones, reducing harvest increases the forest sector C sink compared with BAU through 2050, but by 2100, the C sink is still greater than or equal to BAU in the Temperate Continental ecozone but less than BAU in the Subtropical Humid ecozone. In contrast, increasing harvest reduces the C sink by 2050 in both ecozones, and by 2100, continues to reduce the C sink in the Temperate Continental ecozone while slightly increasing the C sink in the Subtropical Humid ecozone.

4. Discussion

4.1. Comparison of results with other studies

A recent nationwide study by Zhu et al. (2019) concluded that there is limited potential to increase C stocks in forests because analysis of inventory data and modeling, similar to our approach, showed that most forest areas of North America were approaching C saturation and could add not more than 22% more live biomass by 2080, on average. In contrast, we found that by comparing the calculated asymptote of potential C stock with the current median C stock, major areas of Eastern forests could roughly double accumulated biomass over time periods from decades to centuries if protected from harvesting and major disturbances (Table 1). Likely reasons for this discrepancy are that Zhu et al. (2019) failed to consider that reducing partial harvesting in the U. S. East would allow poorly stocked and degraded hardwood forests to recover (Hoover and Heath 2011), and that age-class distributions of eastern forests are much younger on average than forests in other areas of North America. Furthermore, we assumed no changes in climate and natural disturbances in the Eastern U.S., while Zhu et al. (2019) attempted to account for these effects. Also, Zhu et al. (2019) excluded only those inventory sample plots that had evidence of disturbance or logging during the most recent inventory period, while we also excluded sample plots that were understocked and likely reflect disturbances that occurred prior to the most recent inventory period.

Although we assume that eastern forests can continue to accumulate large quantities of C for many decades without significantly greater risks, we note that this view is not universally shared. Concern about increasing risk is primarily focused on projected increases in climate-related threats from wildfire, insects, disease, and drought as highlighted in the most recent assessment of the nation’s forests (U.S. Department of Agriculture, Forest Service, 2023). But as this recent assessment makes clear, these future threats are far more likely to be significant in the Western U.S., whereas the Eastern U.S. where our study is focused is less likely to be affected as frequently or severely. The assessment highlights that most significant future uncertainty in our study region is in the South, based on scenarios of increased harvesting for timber products, and continuing loss of forest land to development, both of which are less likely to affect the North. We also note that the age-class distributions in the Forest Service study, like ours, show that most forests in the East are in their middle ages, implying that there is potential for them to progress to older age classes. Projected biological growth rates in the Forest Service study have similar patterns of decline as our C accumulation growth rates, although ours decline over a significantly longer period of time and never reach a net negative accumulation rate.

Other studies in areas lacking large areas of native forests, such as much of Europe, have concluded that C saturation in live biomass is likely in the near future (Nabuurs et al. 2013; Pilli et al. 2022), but we find that U.S. Eastern forests are not likely to have similar constraints to continued biomass accumulation, reflecting the ability of Eastern

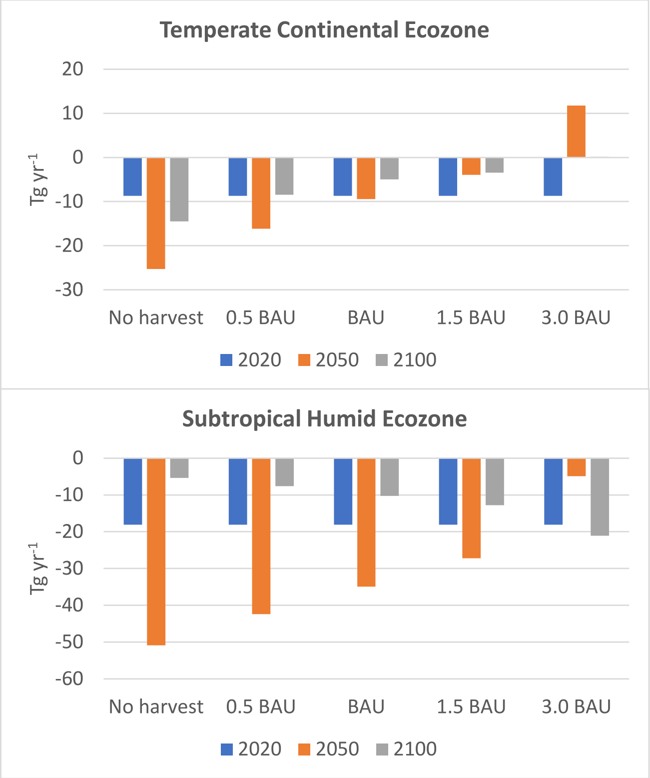


Fig. 8. Past and projected C flux under business as usual and several harvest scenarios (no harvest = 0.0; 50% of BAU harvest = 0.5; 150% of BAU harvest = 1.5; 300% of BAU harvest = 3.0). Values greater than 0 signify a C source, and values less than 0 signify a C sink. Data represent the sum of C fluxes in the forest ecosystem (harvested area plus undisturbed areas), harvested wood products, and impacts of substituting wood for other materials. Accounting for substitution impacts increases the estimated net C sink if harvest increases, and decreases the estimated net C sink if harvest decreases (data shown in supplemental tables S1 and S2).

hardwoods to develop complex structures and species diversities that facilitate long-term successional dynamics (Curtis and Gough 2018).

Our results are consistent with many other studies of national or eastern forests. Pan et al. (2011) developed the first forest age map of North American forests, and the age distributions in the Eastern U.S. clearly highlighted the cluster of forest ages in the middle ages (Northeast and North Central regions) or young ages (Southeast and South Central regions), indicating significant potential for continuing C accumulation over the long term. Brown et al. (1997) concluded that many sawtimber (i.e. middle-aged) stands in the Eastern U.S. could more than double their above-ground biomass (AGB). Lichstein et al. (2009) concluded that substantial late-successional AGB declines are rare in US forests, and that late-successional AGB increases are relatively common, particularly in the eastern US. By reconstructing historical baselines in Wisconsin, Rhemtulla et al. (2008) found that current above-ground C of 276 Tg could potentially rise to 434 Tg statewide. McGarvey et al (2015) demonstrated the potential for dead wood to maintain the sink capacity of secondary forests for many decades to come, an important C pool that increases with forest age and is an important characteristic of old growth.

Similar to other studies (Birdsey et al. 2023; Lichstein et al. 2009; Luyssaert et al. 2008; Pregitzer and Euskirchen 2004), we found that the rate of C accumulation peaks at a relatively young stand age (Fig. 6), followed by a gradual decline in the rate of C accumulation that approaches zero at the oldest ages available in the FIA dataset. The asymptotes of the C accumulation curves appear to be higher than stocks estimated for the set of old-growth samples. Generally, it is likely that the remnant old-growth areas in the East are from different populations of trees than those re-growing on the areas with a history of clearing for agriculture followed by re-establishment of forest cover. Section 4.4 presents some reasons for these differences.

Our baseline estimates of the net C sink on forest land for BAU in the year 2020 are comparable to the sink estimated for forest remaining forest by USDA (USDA 2016). According to that study, the annual C sinks for undisturbed forest in the North and South U.S. were −155 and −216 Mg CO_2 for 2020. Our comparable results are −124 and −224 Mg CO_2 for 2020 for undisturbed forest, BAU case based on data shown in Table S2.

4.2. Potential contributions to policies – targeted reductions in net GHG emissions

There is widespread agreement that reaching net zero GHG emissions by 2050 and sustaining net-zero emissions over the long term will require land management practices that remove CO_2 emitted from sources that are difficult or expensive to control (National Academy of Sciences 2018; United Nations 2015). Globally and for the U.S., it is anticipated that about 10% of the reduction in net GHG emissions must be provided by the land sector in order to achieve net-zero emissions by 2050 (United Nations 2015; White House 2016). Comprehensive studies have typically shown that both globally and within the U.S., forest protection, management, and restoration will have a significant role in sustaining and increasing terrestrial CO_2 removal (Cook-Patton et al. 2021; Fargione et al. 2018). Our results indicate that Eastern U.S. forests can continue to act as C sinks for many decades and likely for a century or more if protected from harvest or disturbance and/or carefully managed to protect existing C stocks and allow future stocks to attain their potential magnitude. As shown in Table 1, Temperate Continental forests could on average continue accumulating C for roughly 200 years, and add an additional 151 Mg ha^{-1} of stored C. Subtropical Humid forests could on average continue accumulating C for roughly 40 years, and add an additional 85 Mg ha^{-1} of stored C. Other studies have come to similar conclusions (Brown et al. 2018; Gunn et al. 2014; Johnsen et al. 2014; Moomaw et al. 2019; Nunery and Keeton 2010), while some have suggested that more intensive management of forests can increase growth and store more C than protecting them from logging and other disturbances (Malmsheimer et al., 2011; Nabuurs et al. 2007); however, we contend that increasing growth without also accounting for the "carbon debt" that occurs when converting middle-aged and older forests to intensively managed commercial forests delays the potential benefits of increased growth by many decades if not centuries in most cases.

Our results clearly show that divergence among alternative scenarios peaks around 2050, and then the alternatives converge or nearly converge by 2100. Thus, the most impactful approaches are different depending on timeframe, which is largely related to the C debt issue. It has been suggested that the importance of the land sector may be greater in the shorter term, since other technological solutions to reducing or eliminating emissions from fossil fuels, and scaling them up to be meaningful, will take some time to evolve (Larson et al. 2021; National Academy of Sciences 2018).

Putting our results into policy context, the potential reduction in net CO_2 emissions is small compared with the annual CO_2 emissions from using fossil fuels that would need to be reduced, but still a significant part of the approximate 10% emission reductions required from the land base to reach net zero by 2050 (Table S3). Our estimated emission reduction by 2050 from stopping harvest over the 73 million ha of middle-aged forests amounts to 117 Mg CO_2 per year, equivalent to about 7% of the emissions from using fossil energy in the two ecozones. By ecozone, reductions compared with fossil fuel emissions are about 10% from the 40 million ha area of middle-aged forest in the Subtropical Humid ecozone and 5% from the 33 million ha area of middle-aged forest in the Temperate Continental ecozone. On the other hand, increasing harvest compared with BAU would have the opposite effect but of similar magnitude for the two ecozones, and considering that it is unlikely that timber harvest would be stopped on private lands without extraordinary measures, avoiding an increase in harvest in these ecozones is the most urgent finding with respect to informing policies for reducing GHGs. And because of leakage (discussed later), it may be that other options for forests that do not reduce harvesting will need to be considered along with net emission reductions from non-forest land uses to attain the full 10% net GHG reductions needed from land management.

On a per unit area basis, stopping harvest would reduce CO_2 emissions by 1.8 and 1.5 Mg ha^{-1} annually on average for the Temperate Continental and Subtropical Ecozones, respectively. On a per capita basis, this is equivalent to about 0.8 and 1.4 Mg annually, for these same ecozones. Fossil fuel emissions of CO_2 in the two ecozones amounted to 1,111 and 512 Mg, compared with 4,595 Mg for the entire U.S. in 2020 (U.S. Department of Energy, 2022). Therefore, emission reduction measures for the land base in these two ecozones are not sufficient for attaining national targets for the land base even though important within the study region.

4.3. *Implications for land managers*

Forests are owned and managed for a wide variety of purposes, and currently, protecting or increasing carbon stock is rather uncommon (Butler et al. 2016). But not all land needs to be optimized for climate mitigation. Commercial forests provide important products that are in high demand now and in the future (USDA 2016), and are typically managed to yield a sustainable flow of wood volume for markets. It is important to note, however, that emerging studies indicate how silvicultural practices for temperate commercial timberlands could be deployed to increase average C stocking without reducing harvest levels (Kauppi et al. 2022; Walker et al. 2023).

On the other hand, there is a vast area of nonindustrial forest land comprising about 100 million ha in the Eastern U.S. (Oswalt et al., 2017) that could be better protected and managed to increase its function as important C stores and sinks. About 69% of this area is poorly stocked with live trees and the potential gains in C stocks are significant (Birdsey 2021; Hoover and Heath 2011).

Some recent analyses have explored the notion of managing forests for old-growth characteristics (Ford and Keeton 2017; Thom et al. 2019). This approach holds great promise for treating the middle-aged forests that are the focus of this paper. Yet deployment of new management practices is currently facing significant barriers including the need for more detailed analyses of mitigation options at regional and local scales, and incentives that can help foster climate-friendly actions, both of which can help modify ownership objectives to improve responses that are typically limited regarding changing forest management practices (National Academy of Sciences 2018; Walker et al. 2023).

4.4. *Data gaps and other uncertainties*

Sampling errors are generally small, less than 10% for each age class, because of the large number of FIA sample plots at the scale of the ecozones in this study. Yet there are insufficient FIA sample plots in the oldest stand age classes to characterize “old growth” or late successional stages of stand development. Modeling errors are typically more significant than sampling errors. For example, the differences between recently used FIA biomass models are significant, averaging 16% nationwide but with larger differences in some regions (Domke et al. 2012; Menlove and Healey 2020). Although our results are robust at the ecozone scale, we have shown here that C accumulation in smaller domains can differ significantly from averages for larger but more heterogeneous domains (Figure S4).

This study did not attempt to account for changes in soil C. There is some evidence that soil C is relatively stable but with some notable exceptions that are not clearly represented by the FIA data because of small soil sampling sizes – only a subset of FIA plots includes soil sampling. Detailed studies have revealed complex responses of soil C to management; for example, harvesting may disturb soil sufficiently to release stored C, depending upon landform and soil taxonomy (Nave et al. 2019). Estimates of soil C changes in old-growth forests are sparse. One study of a small area of China indicated that old-growth forests continue to sequester net amounts of C in soils even if other C pools are declining (Zhou et al. 2006), but this and similar small-scale studies are insufficient to support broad-scale conclusions.

We selected the well-known Chapman-Richards equation to estimate C accumulation rates over time because it predicts both the asymptote value and age at which asymptote occurs. However, as shown by comparing the predicted C accumulation at asymptote with measured C accumulation of old-growth, it is clear that old-growth forests are highly variable in their C accumulation rates and may be lower than we predicted. This is likely because of the poor site quality and heterogeneity of site conditions in which the remnant old-growth stands are still present on the landscape. The sites where remnants of old-growth are still occurring are not likely to be representative of the average sites of whole ecozones, and there may have been undocumented small-scale disturbances to the old-growth stands that have affected their C stocks (Fraver et al. 2009; Lichstein et al. 2009).

Our projections assume that there will be no change in important environmental factors that are known to affect C accumulation: increasing CO_2, climate change, and disturbance regimes to name a few (Houghton 2020; Lichstein et al. 2009; Pan et al. 2011). This means that the asymptote projected by the Chapman-Richards equation bears an uncertain relationship with the old-growth condition that would occur if middle-aged forests were allowed to progress to old-growth status. In general, risks of natural disturbances are lower for many parts of the Eastern compared with Western regions, under both current and most projections of future climate (USGCRP 2018).

We chose to use an accumulation approach to constructing C accumulation curves, which is a variation on the common chronosequence approach that substitutes space for time to get around the paucity of long-term datasets. The accumulation approach adds the average C increments from each period to the accumulated stock of the previous period, and for our study areas produces a greater accumulation curve than simply estimating the carbon stock at each period (figure S5). The reason for this difference is possibly related to past disturbances, which are not explicitly represented in the FIA database except for disturbances that occur during the inventory period. The approach to C accumulation involved focusing on undisturbed plots (see methods) since our scenarios involved assessing only changes in harvest levels, other factors held constant. We attempted to account for historical disturbance that did not happen during the inventory remeasurement period by screening out plots that had poor stocking. If we had included disturbed plots in developing the C accumulation curves, they would have been significantly lower in values (figure S5), although the relative impacts of changes in harvest compared with the baseline would not have been affected so much because disturbances (except for harvest) would have been included in both the harvesting scenarios and the BAU, effectively cancelling out each other. Regardless of the approach to simulating future changes on C stocks, there is uncertainty about how best to represent the expected trajectory of growth given these and other unknowns about natural disturbances and future productivity with climate change.

We used generic displacement factors that are broadly representative of temperate forests (Sathre 2010; Smyth et al. 2017), yet it is well known that there is wide variability in specific comparisons of the embedded emissions of wood and other materials (Chen et al. 2018; Sathre 2010). Furthermore, displacement factors are not static over time especially considering that the amount of energy used to make concrete and steel is expected to decline (Harmon 2019). Therefore, our results that include estimates of impacts of changing harvest on future displacement of other materials or energy sources are meant to be illustrative of the accounting that should be done in future work.

Changing harvest levels may affect the results in several ways that are not easy to quantify. Indirect effects may occur within or outside the study area. Land-use changes could occur in response to increased demand and price for timber products. In Favero et al. (2020), the main driver leading to increasing C sequestration in forests is that rising demand for wood results in higher prices, and landowners will therefore respond by investing in intensive forest management and planting more trees because they are certain that their profit will increase in the future. One of the main underlying assumptions of these types of simulation models is that people have perfect foresight and make rational decisions. According to Abt et al. (2014) who developed a similar economic forecasting model, higher timber prices are assumed to lead to higher land rents, yet the authors state “that there are no studies using post-1997 data to support this assumption.” One of the only studies concluding that higher timber prices induce increases in timberland area or avoid conversion to nonforest use is by Hardie et al. (2000), which uses a land-rent model. One of their main conclusions is that policies affecting land use have different results in different localities, suggesting that many other factors besides price of timber affect land-use decisions.

At significant levels of decreased or increased harvest, it may be necessary to assess impacts beyond the study regions (i.e., leakage), which implies looking at how local/regional demand changes might impact forest product trade flows across broader areas (USDA 2016). This requires both economic analyses to understand how demand would likely impact prices, trade, and forest owner behavior, and linked silvicultural/ecological analyses to understand how forest owner behavior changes would impact forest area, structure, and condition. There is substantial evidence that market leakage, or increasing harvest in one region to compensate for decreasing harvest in another, is a significant concern and needs to be factored into the overall impacts on the atmosphere (Murray et al. 2004). For example, Murray et al (2004) noted that leakage rates for forestry projects that reduce harvest can reduce benefits by roughly 10 percent to 90 percent. On the other hand, increasing harvest within our study area could have the opposite effect of increasing estimated benefits if harvest elsewhere were reduced in response. We did not assess induced effects outside of the study boundaries stated in the methods section because of great uncertainties in the methods and data required for these calculations.

5. Conclusions

We have projected that most Eastern U.S. forests could continue to accumulate C for many decades or several centuries in the absence of harvesting, with relatively low risk of natural disturbances, commensurate with some previous studies. There is high variability in the magnitude and duration of this potential, with Temperate Continental forests having greater potential over longer time periods than Subtropical Humid forests. Results from scenario analysis have clear implications for managing forests to reduce GHGs. In the near term of 20–40 years, reducing harvest will yield the greatest reduction in GHGs. This benefit is proportionately greater in the Temperate Continental ecozone. In the longer term of 80 or so years, scenarios converge towards BAU effects on greenhouse gases, but with differences between biomes. Convergence is faster in the Subtropical Humid ecozone whereas the opposite is likely in the Temperate Continental ecozone. These conclusions are contingent upon assumptions of no changes in ecosystem productivity or disturbance regimes. How middle-aged forests in the Eastern U.S. are managed can affect their contribution to achieving net-zero GHG emissions by 2050 and beyond. Well-stocked forests can continue to accumulate C; poorly-stocked forests can be restored; and management of commercial forests can be improved. In all cases, it would be wise for land managers to consider managing for old-growth characteristics, which could be done with low risk in most areas of the Eastern U.S.

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Author contributions

Birdsey is the PI of the study, compiled the compiled the forest inventory data, and led the writing. Castanho and Houghton parameterized and ran the bookkeeping model and analyzed the output. Savage modeled the growth and carbon accumulation data. All authors contributed to the analysis and writing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data is open access from the USFS, or has been published in peer-reviewed journals.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2023.121373.

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