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A comprehensive data-based assessment of forest ecosystem carbon stocks in the US 1907–2012

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Abstract

The consistent and robust assessment of ecosystem carbon stocks remains central to developing and monitoring climate change mitigation strategies. Here, we investigate the dynamics of forest ecosystem carbon stocks in the conterminous United States between 1907 and 2012 at national and regional levels. We build upon timber volume records from historical forest inventories and use a modelling approach to include all relevant pools, e.g. soil carbon, to derive a comprehensive long-term dataset. We find a consistent increase in forest carbon stocks across the country, from 27 PgC in 1907 to 39 PgC in 2012, with persistent regional variations between western and eastern United States, signalling pronounced land use and land management legacy effects. We identify additional potential to increase forest C sinks in both west and east, on diverging levels. Extended forest C stocks stem from forest biomass thickening i.e. increases in biomass C densities, rather than forest area expansion. Our study reflects the first such effort to collectively understand the effects of environmental change and land management on contemporary biomass C stocks at the national level, and critically engages with ongoing initiatives towards assessing the potential for carbon sequestration in forest ecosystems.

1. Introduction

Forest conservation is important for global climate change mitigation as forests have been identified as the main carbon (C) sink in terrestrial ecosystems, absorbing the equivalent of ca. 60% of global fossil fuel emissions (Pan *et al* 2011). In particular, US forests are one of the most important C sinks across North America (Hayes *et al* 2012). However, whether forests act as C sinks or sources is dependent on the medium and long-term C dynamics in biomass and soils (Loudermilk *et al* 2013). While globally, deforestation is a dominating trend in the tropical regions, forests are growing in many countries of the boreal and temperate zone (Hansen *et al* 2013, Baccini *et al* 2017, Houghton and Nassikas 2018). Forest dynamics are highly diverse among countries and world regions (Köhl *et al* 2015), and forest transitions, i.e. shifts from a phase of net deforestation to reforestation, have been identified in several industrialised and industrialising countries (Meyfroidt and Lambin 2011). Understanding the dynamics of forest transitions and their drivers requires long-term perspectives in order to assess the potential contribution of forests to climate change mitigation.

Here we present a comprehensive long-term assessment of forest carbon stocks in the conterminous United States for the period 1907–2012, investigating the role of long-term dynamics of forest management and C sequestration potential at the sub-national scale. There is a growing stock of literature on US forest C dynamics, using a variety of input data and estimation methods: studies using forest inventories include e.g. Birdsey (1992), Birdsey *et al* (2006); Heath *et al* (2003, 2011); Turner *et al* (1995). Other studies used eddy covariance flux tower data (e.g. Xiao *et al* 2011, 2014), dynamic models (e.g. Hurtt *et al* 2002, Woodbury *et al* 2007, Zhang *et al* 2012, Sleeter *et al* 2018), and book-keeping approaches (Houghton 1999, Houghton *et al* 2000). However, these assessments either cover shorter periods of time (Birdsey 1992, Woodbury *et al* 2007, Heath *et al* 2003, 2011, Zheng *et al* 2011, Xiao *et al* 2011, 2014, Sleeter *et al* 2018), assess forest biomass dynamics only (Birdsey *et al* 2006), or are based on data of area change and extraction (Houghton 1999, Houghton *et al* 2000). Other studies identify diverging trends in the US forest C sink on the regional scale (e.g. Hu and Wang 2008, Novick *et al* 2015, Woodall *et al* 2015b)

Our study presents a new, complementary approach, applying IPCC tier 2 methodology (Eggleston *et al* 2006) to assess long-term changes in forest carbon stocks in soil, litter, dead wood and living biomass, based on state- or regional-level data on forest biomass stands. Accounting for different trajectories of forest change, we quantify changes in biomass C stocks and densities on the sub national-level, for the western and eastern United States separately, and analyse region-specific effects of forest management (i.e. harvest, distance to potential biomass stocks). We identify possible legacy effects influencing current C stock development and discuss potential for further C sequestration in the west and east of the United States.

2. Methods and data

The study assesses forest carbon stocks in the conterminous United States for 15 points in time between 1907 and 2012 based on national, historic and recent forest inventories (full references of forest inventory sources used is provided in the supplementary online material (SOM), available online at stacks.iop.org/ERL/14/125015/mmedia). We considered three different forest types, as defined by the Forest Service (USDA Forest Service 2012): (1) 'timberland'—forest land capable of and used for producing wood crops of industrial quality; (2) 'reserved forests' i.e. productive forests exempt from timber use for conservation purposes (Federal Parks, State Parks, Wilderness areas); and (3) 'other forests' i.e. non-protected forests unsuitable for commercial use. (See SOM for additional details.) Ecosystem C stocks on forests were assessed differently for these forest types (table 1). As main inputs (1907–2012), we used reported forest area data for all forest types defined, and additionally, on area classified as timberland, volume of growing biomass stocks. This allowed us to assess actual increases in forest biomass density. Commercially used 'timberland', covering around 80% of forest area throughout the period, is the best documented forest type. In the period 1953–2012, tree-species specific timber volume data at the state level were aggregated to broad sections 'west' and 'east', consistent with the sub-national classifications as defined by the US Forest Service (figure 1).

A detailed description on estimation methods, coefficients, and simplifications used can be found in the SOM. Here, we describe our principle methodology. Inventory data on the volume of growing stock were used to calculate forest C stocks on timberlands, based on standardised IPCC methods at Tier 2 (Eggleston *et al* 2006). In the period 1907–1945, due to lack of state-level statistics, we used aggregated data on timber stocks in eastern and western sections, provided in contemporary forest inventories, and weighted average IPCC expansion factors, to convert biomass to C stocks. The regular forest inventories from 1953 to 2012 distinguish between 14 softwood and 4 hardwood types on western, and 9 softwood and 18 hardwood species on eastern timberland. Forests in the conterminous US are spread over a multitude of ecological zones (Bailey *et al* 1994, FAO 2001, Eggleston *et al* 2006). Therefore, for this period we applied, for each state, tree species- and region-specific factors for conversion and expansion of biomass, root-to-shoot ratios, and biomass carbon fractions of dry matter. This way we accounted for the influence of both diverging climatic conditions and different tree species. To test our results, we conducted a sensitivity analysis, where we recalculated forest biomass C for each ecological zone within a state separately, using respective expansion factors (see SOM for results and details). We used a modified soil carbon model based on Liski *et al* (2002) to assess soil organic carbon (SOC) on timberlands in the 20 cm topsoil, which account for more than 50% of the SOC in the 1 m topsoil. Following Nabuurs *et al* (2003) we compute SOC, litter, and deadwood stocks based on input data of standing biomass and harvest (converted to C), and on static coefficients on tree compartment mortality, litter and humus decay rates.

For the categories 'reserved forests' and 'other forests', no consistent data on biomass stands were provided in forest inventories. Therefore, we used region and forest-type specific published biomass C per area values to calculate the amount of C stored in live biomass in these forest types for western and eastern US. For 'reserved forests', we extracted 'undisturbed' C biomass density values from Houghton (1999). Similarly, biomass C stocks on 'other forests' were estimated based on average C per area values by Birdsey (1992) for this forest type. We assumed these C densities to remain constant throughout the period.

Specific SOC for 'other forests' and 'reserved forests' in west and east was estimated using default values by Houghton (1999) and IPCC (Eggleston *et al* 2006). Litter and deadwood was computed using the same model as for timberlands by Liski *et al* (2002) but with simplified litter transfer and decay factors. Standing deadwood in all forest types was estimated based on ratios of live trees to standing dead trees for each forest type, derived from Smith *et al* (2003). To create a consistent estimate for the total period 1907–2012,

Table 1. Calculation procedures used to assess ecosystem C stocks in forests.

Forest type	Time period	Primary data used	Spatial scale	Calculation procedure and reference
Commercial timberland	1907–1945	Timber volume, harvest	West and east	Aboveground and belowground biomass C stocks assessed from timber volume using IPCC tier 2 expansion factors, stratified by eco-region and species type (Eggleston *et al* 2006). SOC, litter and deadwood modelled based on standing biomass and harvest (Liski *et al* 2002).
	1953–2012		State-level	
Other forests	1907–1945	Area	West and east	Regional factors for carbon density in above- and belowground biomass for other forests (Birdsey 1992) applied to area. SOC assessed using default values (Eggleston *et al* 2006). Litter and deadwood assessed via (Liski *et al* 2002) model using simplified coefficients.
	1953–2012			
Reserved forests	1907–2012	Area	West and east	Reserved forests split into Federal, State parks and Wilderness areas: regional factors for carbon density in above- and belowground biomass for undisturbed forests (Federal parks and Wilderness) (Houghton 1999); above- and belowground biomass C density for managed parks (State parks) (Nowak *et al* 2013). SOC assessed using default values (Houghton 1999, Eggleston *et al* 2006). Litter and deadwood assessed via (Liski *et al* 2002) model using simplified coefficients.

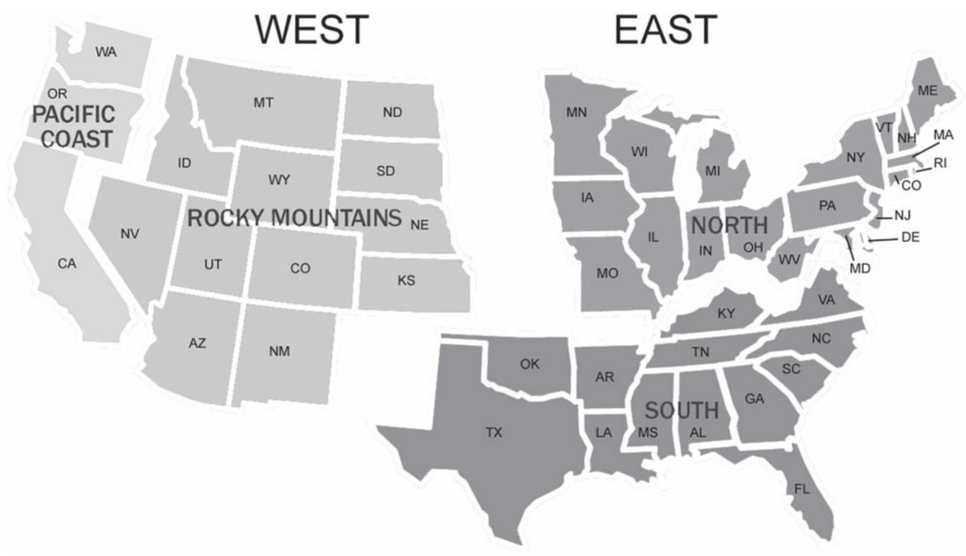

Figure 1. Sub-national split into western and eastern sections of the conterminous US used in this study. East consists of the regions north and south, west of Pacific coast and Rocky Mountains; see SOM for full disaggregation and state abbreviations; USDA Forest Service (2012), edited.

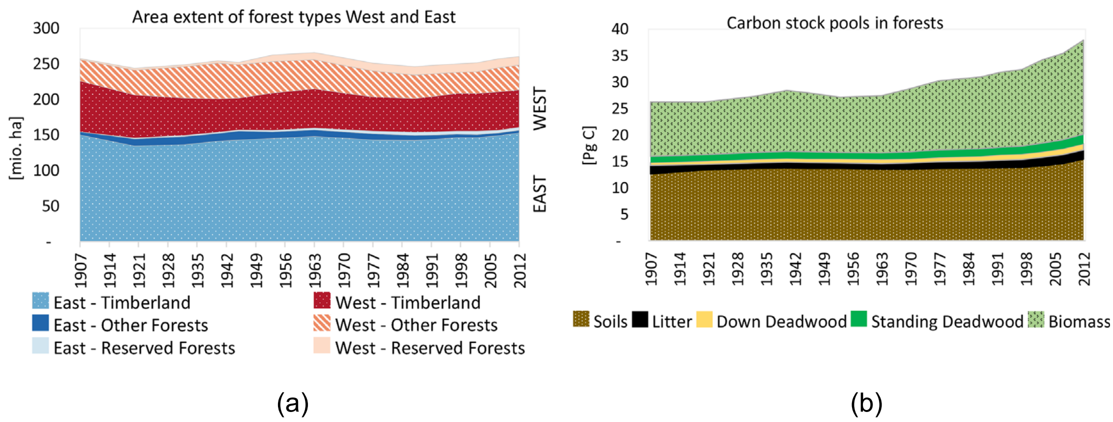

Figure 2. Forest trends in conterminous US 1907–2012. (a) Area extent of major forest types in west and east in million hectare; (b) carbon stocks by pools in all forest types in petagrams (national total).

total forest C stock state level estimates from 1953 to 2012 were aggregated to the sections level.

We use wood yields and potential biomass stocks, i.e. biomass stocks that would prevail in the hypothetical absence of land use (Gingrich *et al* 2007, Erb *et al* 2018), to investigate the current influence of forest management activities, identify possible legacy effects and draw conclusions on possible future carbon sequestration potentials. Region-specific statistics of wood harvest were derived from forest inventories for the period 1963–2012. For earlier years, harvest statistics were reconstructed based on contemporary estimates (see SOM for details). Potential biomass carbon stock estimates in forest types for the west and east were derived from a global spatially-explicit dataset (Erb *et al* 2018) and expanded to belowground biomass using regional weighted average IPCC above-to-belowground ratios (Eggleston *et al* 2006).

3. Results

3.1. Changes in forest area extent and forest carbon stocks in the conterminous United States

Forest area in total (figure 2(a)) did not show strong changes in the observed period, with a peak in the 1960ies and lower values in the 1920s and 1980s, covering 250 Mio. ha ± 5% or one third of the total land surface of the conterminous US. In contrast, carbon stocks increased by 45% during that period (figure 2(b)). Thus, the US forest transition in the 20th century was the result of vegetation thickening, rather than area expansion.

Throughout the period considered, 60%–62% of total US forest area was located in the east. In both sections, timberland was the dominant forest type, although its share in total forest area was significantly higher in the east (>90%) than in the west (69% in

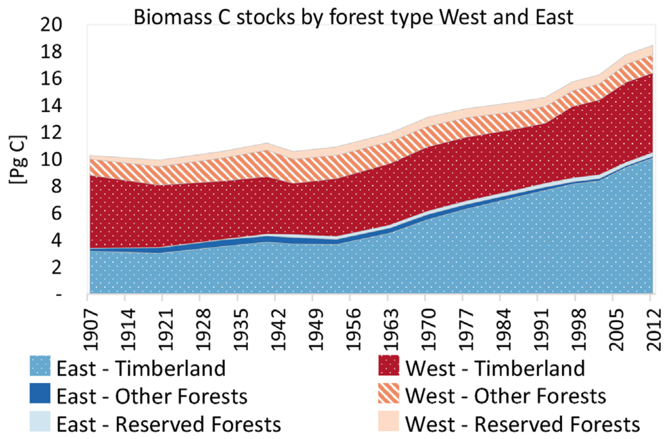

Figure 3. Composition of forests in west and east: biomass carbon in petagrams by forest type in western and eastern conterminous US 1907–2012.

1907 and 53% in 2012). In the west, 'other forests' accounted for a large fraction of total forest area. This type consists of woodland areas with sparse tree stands and low productivity, hosting species such as pinyon-juniper and mesquite, not capable of producing more than 1.4 m^3/ha wood of industrial quality (USDA Forest Service 2012). 'Reserved forests' can be found mainly in the west but represent only a small share of total US forest area (below 5% throughout the century) (figure 2(a)).

Total national forest carbon stocks grew significantly from 27 PgC (petagram carbon) in 1907 to 39 PgC in 2012 (figure 2(b)), mainly owing to increases of forest biomass C, +80% between 1907 and 2012. This represents a net annual C change rate of 116 TgC yr^{-1}. Highest growth rates (0.9%/yr) were found in the last 20 years of the period. Litter and deadwood made up small fractions of total forest C stocks (7% and 8% respectively). SOC accounted for the highest fraction of ecosystem C stocks in forests in 1907 (12 PgC or 46%) but remained almost stable over the entire period, accounting for 15 PgC, or 39% of total forest carbon stocks in 2012. The growth in total forest C on an almost constant area is the result of a strong increase of C density (C per area) over the observed period, from around 104 tC/ha (tonnes C per hectare) to 150 tC/ha, corresponding to an average annual growth rate of 0.35%/yr. Forest biomass density grew even more rapidly in this period, at an average annual growth rate of 0.56%, resulting in almost doubling biomass C densities from 39 tC/ha in 1907 to 71 tC/ha in 2012.

3.2. Differences in forest biomass among west and east

Given the fact that biomass was the main driver of forest C stock changes in the observed period, we focus our analysis on this compartment, examine sub-national trajectories of forest change and investigate the effects of forest management. Firstly, the composition of forests (figure 3) differed significantly between west and east. While in both sections, the highest fraction of forest biomass C stocks was stored in timberlands, their relative contribution was different. In the west, other forests contributed an average fraction of 21% to forest biomass C stocks throughout the period, while another average 9% was stored in reserved forests. This is a strong divergence from the east, where around 90% of C in forest biomass was stored in managed timberlands throughout the period.

Although some sub-regional changes occurred in the areal extent of forest-type groups (Birdsey *et al* 2006), tree species reports in forest inventories from 1953 to 2012 indicate no significant changes in the overall species composition neither in west nor east. The stand of growing stock in western timberlands consisted mainly of coniferous forests (over 90% throughout the period, dominated by Douglas fir), while in the east species were more homogenously distributed (around two thirds deciduous, the rest coniferous).

On the state level, we found carbon densities in the west to be both highest and most unevenly distributed, varying in single states from 35 tC/ha to 168 tC/ha in 2012, as indicated in figure 4. In 1953 densities ranged from 18 tC/ha to 145 tC/ha and deviations (bars in figure 4) from the middle 50% (boxes in figure 4), were even larger (see SOM for results for all states). Highest C densities of the total US in both years were located in the Pacific coast sub-region, comprising of the three states Oregon (139 tC/ha in 1953, 168 tC/ha in 2012), Washington (143 and 163 tC/ha) and California (100 and 105 tC/ha). From 1953 to 2012 this area accounted for an average total of 3.2 PgC, or 65% of all biomass C stored in the west. Compared to the national level this indicates that over 20% of biomass C stocks in all forest types were concentrated on only 3% of the total land area. Biomass C densities in eastern states increased even more significantly (12 tC/ha–52 tC/ha

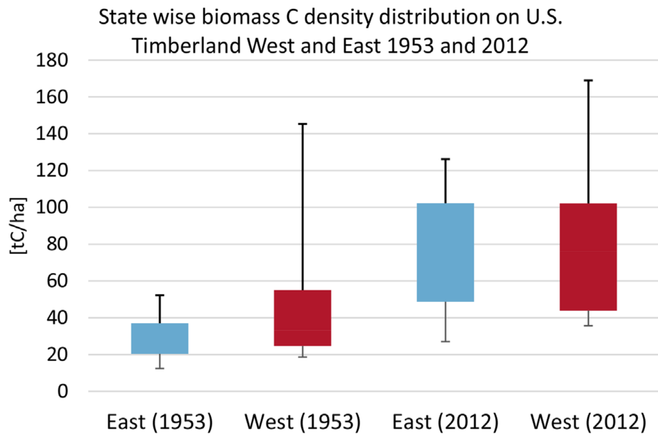

Figure 4. State wise distribution of carbon density on timberland in west and east: boxes represent the biomass C density of the middle 50% of states in the east and west; bars indicate states with lowest and highest densities in the respective section. Densities in tonnes carbon per hectare. Conterminous US 1953 and 2012.

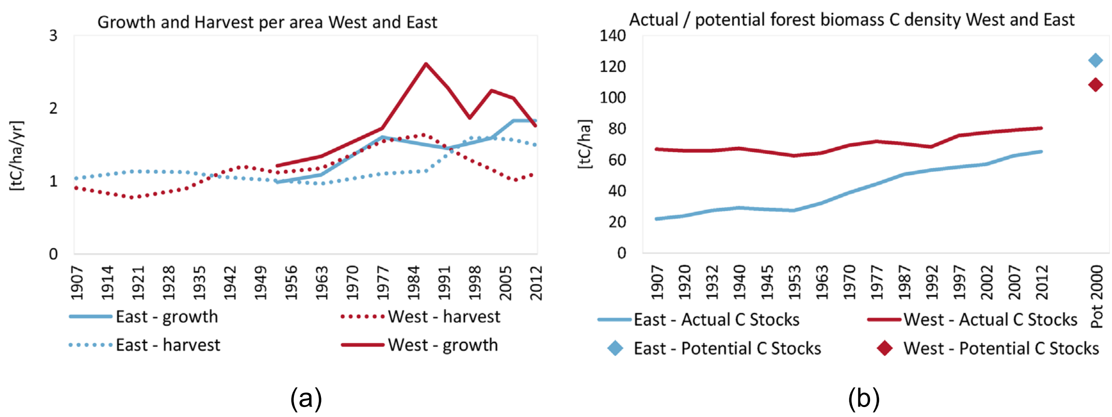

Figure 5. Forest characteristics in west and east (a) net annual growth and harvest in western and eastern timberland, Conterminous US 1907–2012; total C biomass harvest per year (dotted lines) and net annual growth of growing stock (solid lines), in tonnes carbon per hectare. Data for net annual growth of growing stock only available for 1953–2012 (b) trends in total actual forest biomass carbon density (1907–2012) and potential forest biomass carbon density (year 2000) in tonnes carbon per hectare in eastern and western conterminous US.

in 1953, 27 tC/ha–126 tC/ha in 2012) and were distributed more evenly—deviations from the middle 50% of all eastern states were much smaller than in the west at both cuts of time, as indicated in figure 4.

3.3. Forest management in west and east

We investigate the possible contribution of forest management to biomass C dynamics in west and east by comparing wood harvest to forest regrowth, and actual biomass densities on forests to potential biomass densities, all of which show different trajectories in the respective sections.

The trend of timber yields in both sections was at a similar level of 1–2 tC/ha/yr throughout the observed period (figure 5(a), dotted lines). However, we observe different trajectories in east and west. In recent decades timber yields increased to higher levels in the east. In the west, a decline in yields since the 1990s can be observed. The stable extraction rates thus do not explain long-term increases in biomass stocks in either section. We compared harvest to net annual growth of growing stock, defined by the Forest Service (Oswalt *et al* 2014) as the increment of net volume of live trees plus the net volume of young trees reaching the size class of timberland growing stock. No consistent data were available before 1953, but growth rates at the national level in the 1920s were half the rates of extraction at that time, and stabilised only in the 1950s due to reduced harvest and improving growth rates (Smith *et al* 2004). In the east, annual net growth per area exceeded harvest per area after 1953 (growth was 13%–45% above harvest levels) (figure 5(a)), resulting in a strong in overall stock (figure 5(b)) until the beginning of the 1990s, when growth and harvest rates converged. The further trend shows an increase in growth and a small decline in harvest. In the west, a similar pattern can be found: net growth has exceeded harvest from 1953 onwards, but on a lower level than in the east. This trend continued until the end of the 1970s, followed by a short phase of strong increase until the mid 1980s. Afterwards both harvest and growth declined. In the last 5 years observed, harvest in the west slightly increased while growth declined. In the east the opposite happened and net growth reached western levels.

Although our results show a thickening of actual forest biomass in both west and east, trajectories of forest biomass densities in the two sections differ from each other (figure 5(b), solid lines). Western forests throughout the observed period stored the highest amounts of forest biomass carbon per unit area, ranging from 67 to 80 tC/ha. Starting from around the beginning of the 1990s we see an increase in western forest biomass C densities, to over 80 tC/ha in 2012, corresponding to a growth rate of 1% per year. By contrast, forest biomass C density in the east started to increase much earlier, from 1953 onwards, tripling over the study period, from 22 tC/ha in 1907 to 65 tC/ha in 2012. A comparison of the distance between actual forest biomass C density and potential biomass C density at the sectional level (figure 5(b)) reveals that western forests are much closer to their potential (74% of the theoretical potential C biomass stocks in 2012) than their eastern counterpart (53% in 2012). However, the potential biomass stocks in the west are lower than in the east (108 tC/ha and 124 tC/ha, respectively). We observe a significantly stronger growth during the 105 years studied in the east, from below 20% to more than half of the maximum potential, corresponding to a growth rate of 1%/yr compared to 0.18%/yr in the west. This divergence is the result of several factors. Firstly, the different compositions of forest types play a pivotal role: A considerable fraction of actual biomass C stocks in the west is either located in low productive other forests or in protected unmanaged forests, which might already be close to their theoretical potential. In the east, in contrast, commercial forests dominate, which on average show a relatively larger distance between actual and potential stocks, owing to more intensive uses.

4. Discussion

Our results confirm, as demonstrated by Ramankutty *et al* (2010), that over the course of the 20th century no major forest area expansion happened in the US, in contrast to earlier studies (e.g. Clawson 1979, Williams 1992) which interpret the regrowth of forests as a result of large scale abandonment of agricultural land across the US. Instead, we find an increase in total forest C density, driven mainly by changes in C density on commercial timberland, very likely resulting from a recovery of past depletion. Furthermore, on a sub-national level, we find major variations between west and east.

In the west, timberlands, although representing a smaller share of the total, are much denser stocked than in the intensively managed east, where we find largely depleted forests at the beginning of the observed period, large scale tree planting and increasing net annual growth rates. These findings were similar but significantly less pronounced in the west. However, timber extraction over the 100 years observed remained high in both sections of the US, although the purpose for harvest changed: wood remained an important source for energy roughly until the beginning of the 20th century. Thereafter fossil fuels made the use of fuelwood almost obsolete. However, wood extraction remained on constant levels or even increased, caused by the emerging lumber industry, and later by the rising demand for pulp, veneer and other products (MacCleery 1993). The fact that fuelwood lost its importance as source of energy suggests that increasing use of fossil fuels (Gierlinger and Krausmann 2012) might have been an additional crucial prerequisite enabling regrowth of US forests. This hypothesis suggests the carbon sink in regrowing forests is associated with lowered fuelwood energy demand due to expanded use of fossil fuels, similar as Erb *et al* (2007) described for Austria. Increases in extraction and biomass growing stocks at the same time seem to have been enabled by a legacy of forest overuse in the past (Gingrich *et al* 2007, Erb *et al* 2008). The very low initial C stocks at the beginning of the studied timeframe in standing biomass in eastern and, to a lesser extent, also in western forests suggest that extraction may have been very intensive prior to the observed period. This hypothesis is in line with long-term analysis of forest management in the US by Birdsey *et al* (2006) who indicated that forest and wood products played a pivotal role in the strong development of basic infrastructure and the provisioning of fuelwood for the country at least until the end of the 19th century. Therefore, the yields observed from 1907 onwards could represent a more sustainable management than previous extraction rates in the east: starting from largely degraded forest ecosystem leaves more room for enhanced biomass growth. Additionally, as Clawson (1979) implies, the Forest Service may in the past have underestimated actual growth rates in their projections of future timber supply. Hence tree planting was recognised as an important countermeasure to meet projected demand and deliberately encouraged forest production (United States Forest Service 1958). As a result, the area of timberland replanted with trees has increased significantly since the 1950s in the eastern section, mainly in the southeastern sub-region (Oswalt *et al* 2014). Together, past depletion, underestimation of annual increments, and management activities aimed to increase stocks could be the explanation for the significant accumulation of C in forest biomass; This also underlines the importance of management, precisely the interlinkage between net biomass increment and harvest (Clawson 1979).

We find different climate change mitigation potentials in the two sections of the US: both the distance from the maximum potential and regrowth in the east are higher than in the west. This may possibly be caused by higher extraction rates in the past, resulting in depleted stocks at the beginning of the observed period followed by large-scale reforestation efforts throughout the rest of the century (Oswalt *et al* 2019). This led to different demographic compositions of forests in the US: eastern, opposed to western forests, are dominated by young-growth trees, resulting in high forest biomass growth rates in this section. Regrowing forests in the US in the 20th and early 21st century represent a net C sink. According to our results, potential for additional 10 PgC of biomass C sequestration in eastern and almost 8 PgC in western forests exists. Despite this extra potential, we identify several future challenges for future GHG mitigation: Enhanced biomass growth, influenced by climate change, seems to be limited (Zhu *et al* 2018)—early saturation of the forest biomass carbon sink has already been detected in Europe (Nabuurs *et al* 2013). Increased biomass growth might even shorten tree lifespans, therefore nullifying additional C sink gains (Büntgen *et al* 2019). Possible additional C sequestration in western forests could be obstructed by recurring disturbances like wildfire and bark beetle outbreaks (McKinley *et al* 2011) which are more common in this section (e.g. Parker *et al* 2006, Masek *et al* 2013). Disturbances have increased in recent decades (Westerling 2006, Mantgem *et al* 2009), strongly influenced by rising temperatures causing severe draughts (Berner *et al* 2017). Temperatures are expected to increase even further during the 21st century, therefore favouring the occurrence of natural disturbances (e.g. Flannigan *et al* 2000, Bentz *et al* 2010, Littell *et al* 2010). While the number of wildfires has decreased for decades, their severity (area burned) has increased substantially, a trend that will possibly continue (Oswalt *et al* 2014, Barbero *et al* 2015). Our method did not allow us to explicitly identify these effects but the analysis of net changes in forest inventories indirectly accounts for these factors (Heath *et al* 2011). National Carbon emissions in the United States from fossil fuel burning, cement production and gas flaring alone amounted to 1396 TgC in 2012 (Jacobson *et al* 2018), whereas the rate of C absorbed by forests from 2007 to 2012 was as high as 343 TgC yr^{-1}. Obviously, this implies that besides reforestation and forest management, change in policies aimed at reducing US GHG emissions in all economic sectors are needed. According to our results there is still a large C sequestration potential. However, in the light of increasing disturbances, heat-induced increasing tree-mortality (Allen *et al* 2010) and possible limitations to growth of the forest C sink, it remains uncertain whether this potential can be achieved.

Our results show a growth in total forest C stocks in the conterminous US by 15% during the century observed. This corresponds to a net annual sink of 116 TgC yr^{-1} from 1907 to 2012. Our assessment represents a novel data-driven analysis of forest C stocks and complements other studies investigating the sink capacity in US forests, based on multiple assessment procedures (King *et al* 2015). In order to test the robustness of our approach, we compare our findings to other studies, breaking down our time period of analysis to match with other research (table 2). A stock of literature is centred around the roughly 10 years from the beginning of the 1990s until around 2000: estimates range from 180 to 230 TgC yr^{-1}. Our result of 227 TgC yr^{-1} for the period 1992–2002 fits well within this range. However, studies focusing on all carbon pools, forest types and longer time-periods are less common. For the years 1975–2010, Sleeter *et al* (2018) estimate 220 TgC yr^{-1}, slightly higher than our result of 216 TgC yr^{-1} for a similar period. Heath *et al* (2003) estimate 164 TgC yr^{-1} for the period 1963–1997, 17 TgC yr^{-1} above our values for the same period, probably caused by the inclusion of C in organic soils in their study.

Our estimates for C stocks in all pools in comparison with other studies remain generally in line with their outcomes, signalling the robustness of our methodology and the reliability of our results. This procedure is aimed at identifying the degree of (dis-) agreement between studies, and thus uncertainty across estimates. We tested our results by conducting a sensitivity analysis, assessing the impact using different IPCC conversion factors would have had on our estimate. The application of the lowest factors would lead to an 8% lower result, the application of the highest factors to a 6% higher result. (see SOM for details). Noticeable deviations from other studies in SOC results may be explained by our assumption that SOC densities in other and reserved forests remained static over time. Sleeter *et al* (2018) estimate 27 PgC in soils, higher than all other cited studies (15–17 PgC). This may be explained by the fact that they include SOC to a depth of 2 m, opposed to the other studies (max. depth 1 m). Although the majority of SOC is stored in approximately the first 40 cms of soils, inclusion of depths down to 3 m may increase SOC measurements by 1 to 2 times (Jobbágy and Jackson 2000, Wang *et al* 2004). Heath *et al* (2011) included estimates for Alaska in their C stock assessment, hence explaining their slightly higher results. The forest service estimated total C stocks of 38 PgC in 2014, using a forest dynamics module coupled with a land use dynamics module. Despite the difference in estimation procedures, we were able to produce almost the same result (39 PgC in 2012) using IPCC expansion factors. While our assessments of C stocks on reserved forests and other forests relies on much poorer data sources than those on timberlands, the limitations of input data quality do not result in significant deviations from other assessments.

Table 2. Comparison of results to other studies. (a): net annual C sink estimates, various periods (b): single year carbon stocks in all C pools. Conterminous USA *A = aboveground biomass; B = belowground biomass.

Estimate this study ($TgC\ yr^{-1}$)	Period this study	Estimate other study $TgC\ yr^{-1}$	Period other study	Estimation method
(a)				
227	1992–2002	230 (Hurtt *et al* 2002)	1990–1999	Ecosystem demography+Miami land-use model
		180 (Zheng *et al* 2011)	1992–2001	Carbon change per area
		210 (Zhang *et al* 2012)	1992–2001	Terrestrial ecosystem C cycle model
216	1977–2012	220 (Sleeter *et al* 2018)	1975–2010	Dynamic global Vegetation model + Land-use and C scenario model
147	1963–1997	164 (Heath *et al* 2003)	1963–1997	Biomass and carbon conversion and expansion factors

(b) C stocks	This study (PgC) in 2012	(Sleeter *et al* 2018) (PgC) in 2010	(Woodall *et al* 2015a) (PgC) in 2014	(Heath *et al* 2011) (PgC) in 2008
Estimation method	IPCC biomass and carbon conversion and expansion factors	Dynamic global Vegetation model + Land-use and C scenario model	Plot level Forest dynamics and land use dynamics model	C densities applied to FIA inventory plots
Data source	USFS Forest Inventories	USGS Land Cover, National Land Cover Database, North American Forest Dynamics, Monitoring Trends in Burn Severity, Protected Areas Database, North American Forest Age	USFS Forest Inventories	USFS Forest Inventories
Living Biomass (A + B)*	18	18	17	20
Soils	15	27	16	17
Litter	2	2	3	5
Deadwood	3	4	2	3
Total	39	50	38	45

5. Conclusions

We present a new comprehensive assessment of US forest carbon stocks over the past century, based on timber volume reports from forest inventories. The combination of simple calculation methods and detailed forest statistics produced estimates quite well in line with previous assessments. This shows that the IPCC default methods are suitable for producing solid results if sufficient input data are available, which might be relevant for studies assessing C stocks in other countries, where forests play a central role for the terrestrial carbon budget. This might help increasing comparability between different studies.

We showed that the forest transition of the conterminous US is driven by increasing C densities due to restocking on relatively unchanged areas. The analysis revealed a strong divergence between west and east, and highlights the importance of forest composition and long-term impacts of forest management on associated C budgets. Commercially used forests appear to have the capacity to regrow at a faster pace than forests with higher shares of less used or protected ecosystems, but only due to large-scale forest depletion in earlier periods. In addition to the past depletion of forests, the energy transition from fuelwood to fossil fuels might have been a central prerequisite for the observed biomass C thickening. A long-term perspective incorporating all forest types and pools, identifying the impacts and effects of past managements proves to be useful for understanding developments in present day C stocks but also for interpreting the potential to increase the C sink in forests in the US. We find different potentials for additional forest C stocks in both sections, although reforestation through management is less likely to happen in the west than in the east, due to the closer distance to potential C stocks and the smaller amount of managed forests. In view of the new conditions caused by climate change, counter measures against increasing natural disturbances like fire-monitoring and pest-control might be critical challenges for future forest management. Additionally, substantial emission cuts in other economic sectors should be prime targets for future policies. However, the influence of natural disturbances and the dynamics between harvest and increment on potential C stocks need to be better understood and require further empirical analysis, which was beyond the scope of this study.

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Data availability statement

The data that support the findings of this study are openly available at https://doi.org/10.5281/zenodo.3520849.

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