Climatic Change (2017) 144:207–220
DOI 10.1007/s10584-017-2038-5

Forest sector carbon analyses support land management planning and projects: assessing the influence of anthropogenic and natural factors

Alexa J. Dugan[1] · Richard Birdsey[1] · Sean P. Healey[2] · Yude Pan[1] · Fangmin Zhang[3,4] · Gang Mo[4] · Jing Chen[4] · Christopher W. Woodall[1] · Alexander J. Hernandez[5] · Kevin McCullough[1] · James B. McCarter[6] · Crystal L. Raymond[7] · Karen Dante-Wood[8]

Received: 20 January 2017 / Accepted: 17 July 2017 / Published online: 27 July 2017

Abstract Management of forest carbon stocks on public lands is critical to maintaining or enhancing carbon dioxide removal from the atmosphere. Acknowledging this, an array of federal regulations and policies have emerged that requires US National Forests to report baseline carbon stocks and changes due to disturbance and management and assess how management activities and forest plans affect carbon stocks. To address these requirements with the best-available science, we compiled empirical and remotely sensed data covering the National Forests (one fifth of the area of US forest land) and analyzed this information using a

Electronic supplementary material The online version of this article (doi:10.1007/s10584-017-2038-5) contains supplementary material, which is available to authorized users.

✉ Alexa J. Dugan
adugan@fs.fed.us

1 USDA Forest Service, Northern Research Station, 11 Campus Blvd, Suite 200, Newtown Square, PA 19073, USA

2 USDA Forest Service, Rocky Mountain Research Station, 507 25th St, Ogden, UT 84401, USA

3 Nanjing University of Information Science and Technology, Nanjing, Jiangsu 210044, China

4 Department of Geography, University of Toronto, Toronto, ON M5S 3G3, Canada

5 Utah State University, Logan, UT 84322, USA

6 Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC 27695, USA

7 Seattle City Light: City of Seattle, 700 5th Avenue, Suite 3200, Seattle, WA 98124-4023, USA

8 USDA Forest Service, Washington Office, 201 14th St, SW, Washington, DC 20250, USA

carbon modeling framework. We demonstrate how integration of various data and models provides a comprehensive evaluation of key drivers of observed carbon trends, for individual National Forests. The models in this framework complement each other with different strengths: the Carbon Calculation Tool uses inventory data to report baseline carbon stocks; the Forest Carbon Management Framework integrates inventory data, disturbance histories, and growth and yield trajectories to report relative effects of disturbances on carbon stocks; and the Integrated Terrestrial Ecosystem Carbon Model incorporates disturbance, climate, and atmospheric data to determine their relative impacts on forest carbon accumulation and loss. We report results for several National Forests across the USA and compare their carbon dynamics. Results show that recent disturbances are causing some forests to transition from carbon sinks to sources, particularly in the West. Meanwhile, elevated atmospheric carbon dioxide and nitrogen deposition are consistently increasing carbon stocks, partially offsetting declines due to disturbances and aging. Climate variability introduces concomitant interannual variability in net carbon uptake or release. Targeting forest disturbance and post-disturbance regrowth is critical to management objectives that involve maintaining or enhancing future carbon sequestration.

Keywords Forest carbon · Forest inventory · Ecosystem model · Climate change · National Forests

1 Introduction

Forest ecosystems and harvested wood products represent the largest terrestrial carbon (C) sink in the USA and globally, persistently offsetting about 14% of the nation's carbon dioxide (CO_2) emissions (USEPA 2015) and about one third of global CO_2 emissions from burning fossil fuels (Pan et al. 2011). The current C sink is largely the result of forest recovery from widespread clearing for agriculture and intensive harvesting during the nineteenth century and is a testament to the resilience of forests (Birdsey et al. 2006). Yet as forests grow older and slower and with threats from climate change, air pollution, deforestation, and increasing wood demand, the persistence of this C sink is less certain (Wear and Coulston 2015). Conversely, climate and atmospheric chemistry changes may have significant positive effects on productivity and C accumulation in some regions (Zhang et al. 2012). European countries are experiencing a similar mix of influences and impacts that is becoming typical of the world's temperate-zone countries (e.g., Bellasson et al. 2011).

Given these trends and their uncertain aggregate effects, international and national policies are being implemented to reduce anthropogenic threats and enact sustainable forest management practices (e.g., USDA Forest Service 2010; US Department of State 2015; UNFCCC 2015). There is considerable potential to reduce losses or increase C stocks by reducing deforestation or increasing afforestation, improving forest management, and substituting wood products for more energy-intensive building materials or fossil fuels (e.g., Perez-Garcia et al. 2005; McKinley et al. 2011; Ter-Mikaelian et al. 2015). The appropriate application of these policies will vary by ownership so that mitigation activities can be integrated with other land-use objectives to ensure that forest uses such as timber production and water supply are not reduced and to confirm that gains in C stocks or reduced greenhouses gas (GHG) emissions are real and verifiable (Sample et al. 2010).

Public lands have well-defined and nationally consistent policies that govern management activities, and because of their large area, they could have significant effects on the future of the US forest C sink (Dilling et al. 2013). The US Forest Service manages approximately one fifth (59 million ha) of US forest land containing roughly one quarter of all forest C stocks (Heath et al. 2011a). Recognizing this significance, federal policies have been enacted to improve assessments of impacts of management activities on C stocks, with an emphasis on reporting baseline C stocks and changes over time due to disturbance and management, and potentially in the future, incorporating C stewardship with management objectives (USDA Forest Service 2010).

In this study, we take advantage of advances in availability of data and analysis methods to conduct C assessments at the landscape scale typical of management units such as National Forests, using a consistent approach across the USA. Previous analyses of relative impacts by anthropogenic and natural factors at larger scales are less relevant to land managers, who require finer differentiation of patterns and processes along ownership lines and that reflect local climate variability. Although there have been various forest C modeling studies at national (e.g., Zhang et al. 2012) and regional scales (e.g. Law et al. 2004; Pan et al. 2009), these studies generally employ varying methods, models, and time scales. Operational-scale C assessments across the range of sites, environments, and management histories using standardized methods have been lacking in the USA.

To facilitate C reporting and inform management decisions, we developed a nationally consistent C modeling framework based on a management-oriented landscape scale for US National Forests. Here, we compare input data and model results for a selection of the 154 National Forests that represent geographic and climatic variations in addition to varying ecosystem and disturbance processes. These forests include the National Forests in Florida (NFF), Medicine Bow-Routt National Forest (MBR) in north-central Colorado and southern Wyoming, Plumas National Forest (PNF) in northeastern California, and Ottawa National Forest (ONF) in Michigan's Upper Peninsula. By presenting and interpreting model results from several diverse National Forests, we illustrate how this framework provides useful information for characterizing C dynamics and the relative contributions of driving factors, while also fulfilling Forest Service policies (USDA Forest Service 2010). By separating direct impacts of land management decisions from historical influences, changing natural disturbance regimes and atmospheric conditions, the results account for the net effect of specific actions. We show how the effects of different driving factors are regionally variable and provide our views on the prospective future of the terrestrial C sink in the USA given the observed trends for these selected National Forests.

2 Summary of methods: a carbon modeling framework and data integration

We integrated remotely sensed and field-sampled data within a forest C modeling framework (Fig. 1) to provide a comprehensive assessment of current C stocks and recent trends and to distinguish relative impacts of land management and natural disturbances on C budgets within the forest ecosystem of each US National Forest. Specifically, we estimated (1) baseline C stocks via the Carbon Calculation Tool (CCT); (2) effects of disturbances on C storage and emissions using the Forest Carbon Management Framework (ForCaMF); and (3) long-term relative effects of disturbance and non-disturbance factors on C accumulation using the Integrated Terrestrial Ecosystem Carbon (InTEC) model. Regional-scale analyses of harvested wood products were conducted in related studies (e.g., Stockmann et al. 2012). Forest C assessments at this fine, management-unit scale require high-resolution, spatially explicit

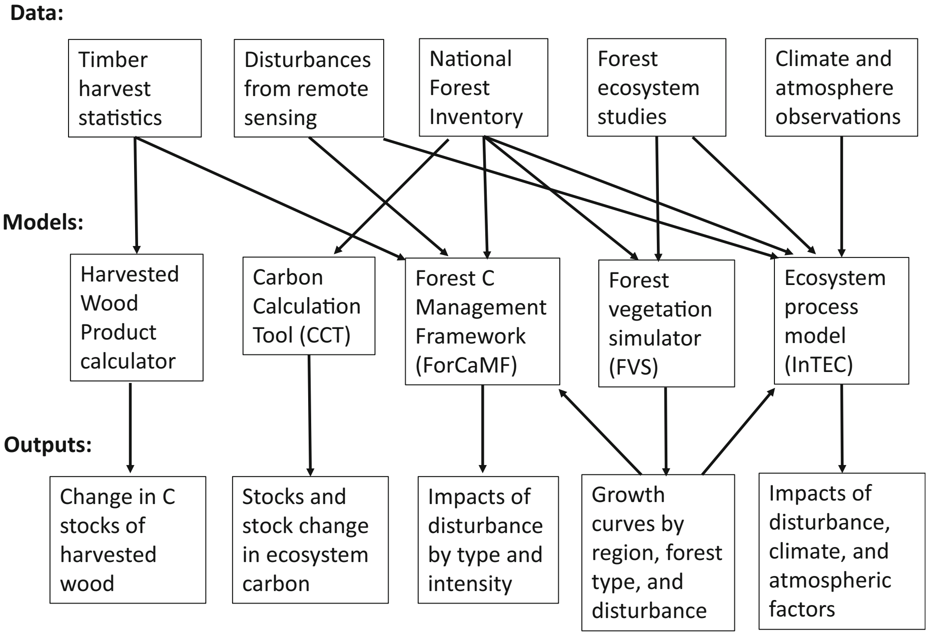

Fig. 1 General scheme for integrating data and models, and main outputs. Analyses of carbon in harvested wood products were conducted in related studies (e.g., Stockmann et al. 2012)

datasets. Because of diverse modeling objectives and variety of independently collected data inputs, an integrative approach is necessary to accurately estimate total C stocks and rates of change and to separate influences of different factors on C storage. We describe briefly the models and data and provide further details in the Electronic supplementary materials (ESM) 1.

The CCT model summarizes available Forest Inventory and Analysis (FIA) data collected on field plots at a density of approximately 1 plot/2430 ha across the country (Bechtold and Patterson 2005). CCT calculates C stocks and changes from FIA tree-level data from at least two points in time using allometric models (Smith et al. 2010; Woodall et al. 2011a). FIA data can be used for estimating total C by forest type, age class, and other categories and tracking net changes in C stocks. However, because FIA data in many parts of the country is collected at a 10-year interval and many plots have been measured only once with the current design, the inventory's current usefulness in explaining disturbance and climatic or atmospheric trends is limited unless supplemented with additional analyses from ecosystem experiments or models (e.g., Bellasson et al. 2011; Fang et al. 2014).

The ForCaMF model integrates FIA data, disturbance maps, and an empirical forest dynamics model, the Forest Vegetation Simulator (FVS) (Crookston and Dixon 2005) to assess impacts of different disturbances (Healey et al. 2014, 2016). To examine disturbance impacts by type and intensity, ForCaMF employs manually verified maps of disturbance type and magnitude created by integrating time series of Landsat satellite imagery (e.g., Huang et al. 2010), high-resolution aerial imagery, and agency records of harvest, fire (Eidenshink et al. 2007), and insect activity (Johnson and Wittwer 2008). ForCaMF also generates regionally representative forest C storage trajectories for alternative disturbance and management scenarios (Raymond et al. 2015). Modeling timescales of CCT and ForCaMF were constrained to recent decades (since 1990) when Landsat and FIA were available. ForCaMF does not address changes in soil C, which refers to subsurface organic matter including soil microbial layers up to 1 m in depth, excluding litter, duff, and fine roots (Woodall et al. 2011a).

Therefore, to further build upon CCT and ForCaMF, we used InTEC—an ecosystem process model which integrates stand-level FIA data, the Landsat disturbance product used in ForCaMF, and additional datasets such as climate records and measurements of CO_2 and nitrogen (N) deposition to determine the relative effects of environmental variables and disturbances on C dynamics since 1950 (e.g., Zhang et al. 2012). InTEC is driven by stand age, serving as a proxy for historical disturbance (Pan et al. 2011), plus forest-type maps and net primary productivity (NPP)—age relationships which together determine regrowth following disturbances and were all partly derived from FIA data. InTEC also tracks complex soil C and nutrient dynamics.

Although the models and data have differences, all were calibrated to FIA observations which have been compiled according to US GHG inventory standards (USEPA 2015). Reliance on FIA data and conformance with international reporting standards enhances agreement between model results and ensures that results are well grounded in observations. While each model provides unique information and has implicit value on its own, integration of these modeling approaches and data inputs achieves a more comprehensive assessment of forest C trends and influences than the individual models alone. More thorough descriptions of the data and models are available in ESM 1. Using an example of the National Forests in Florida (NFF), we provide more thorough, step-by-step descriptions of how the input data and models are integrated in the supplemental materials and illustrated in Figs. S1, S2, S3, S4, S5, and S6.

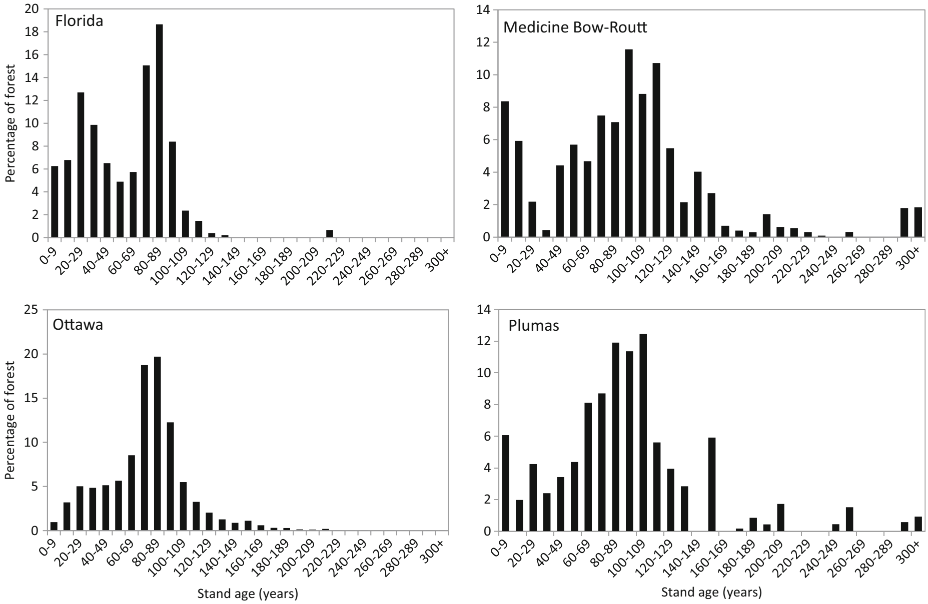

Fig. 2 Stand-age distributions for National Forests in Florida and Ottawa, Medicine Bow-Routt, and Plumas National Forests. Age-class distributions may include multi-aged stands in which average ages were used in the models

3 Results for selected national forests

Here, we present the analysis of input data and model results for the four selected US forests.

3.1 Stand age and disturbance effects

For all four forests, stand-age distributions developed from FIA datasets are characterized as uneven with unimodal or multi-modal peaks of stand establishment, indicative of recovery after stand-replacing disturbances or abandonment of agricultural lands, among longer periods of lower establishment rates (Fig. 2). For the two western forests, early establishment pulses

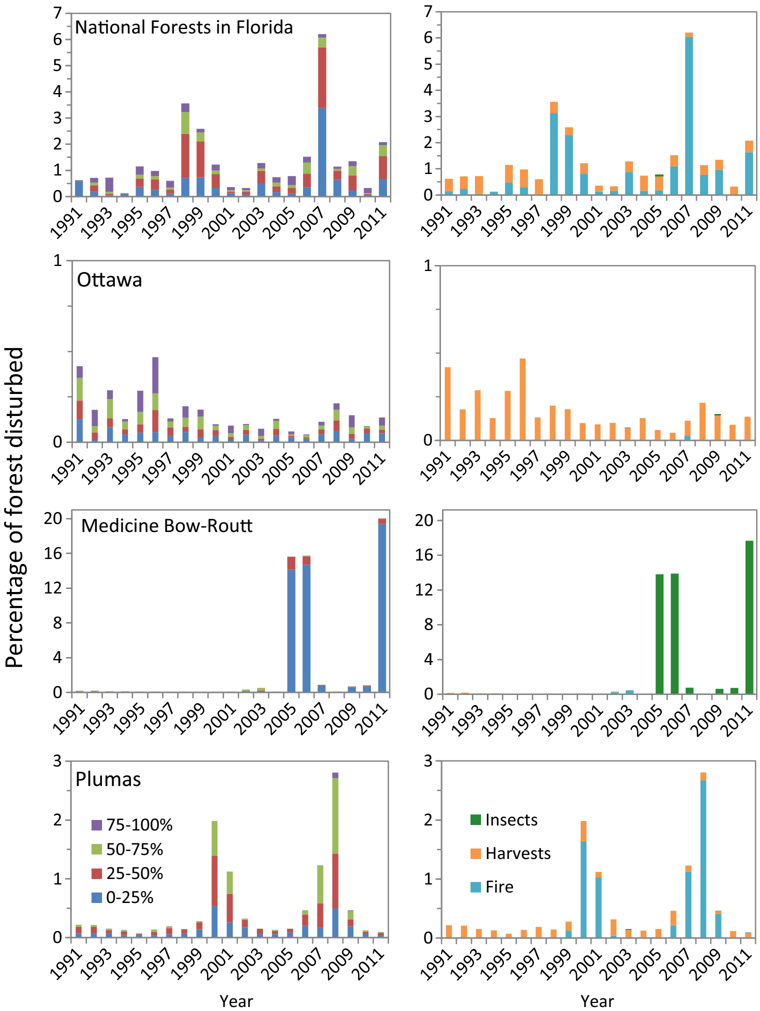

Fig. 3 Percentage of forest area disturbed by intensity class defined as the percent change in canopy cover (*left*) and disturbance type (*right*) for National Forests in Florida and Ottawa, Medicine Bow-Routt, and Plumas National Forests

occurred roughly 80–120 years ago (1890–1930). In the two eastern forests, a similar early pulse occurred 70–90 years ago (1920–1940). These stands were most productive when they were young- to middle-aged (e.g., Fig S1b; He et al. 2012), around the mid-1900s, though the exact timing of highest productivity is dependent on forest type and region.

Recently, increased areas of young stands are related to disturbances shown in the Landsat record. For instance, stand-age distributions for PNF and MBR show spikes in establishment within the last 20 years (1990–2010), due to recovery after large and/or higher-severity disturbances (Fig. 3). PNF experienced relatively large, moderate- to high-severity fires in 2000 and 2008. Fire caused the lost potential storage of roughly 3.3 Mg C ha^{-1} from 1990 to 2011 (Fig. 4), and when combined with aging effects, caused a decline in accumulated C beginning in the 1980s (Fig. 5). Though MBR has experienced mostly low-severity insect outbreaks, they have affected >50% of the forested area in recent years (Fig. 3), prompting extensive recovery (Fig. 2), the loss of nearly 17 Mg C ha^{-1} (Fig. 4), and a decline in accumulated C (Fig. 5). In contrast, CCT results indicate that both MBR and PNF experienced small increases in C density from 1990 to 2013 (Fig. S7). ONF and NFF lack this recent pulse likely due to relatively low-intensity, occasional disturbances (Fig. 3) that maintain a stable C density (Figs. 4 and 5).

A period of enhanced productivity is indicated by increases in C accumulation attributed to disturbance and regrowth during the 1950s and 1960s (Fig. 5). As stands aged further, productivity declined and stabilized (e.g., Fig. S1b), causing the reduction in C accumulation during the late 1900s and early 2000s.

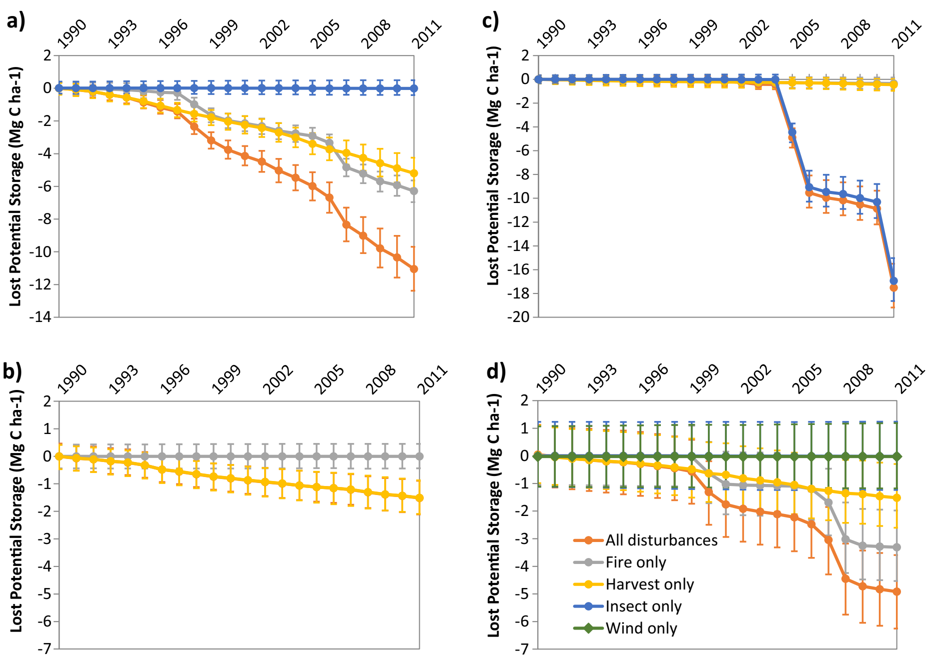

Fig. 4 Cumulative impact of disturbance on carbon stocks for **a** National Forests in Florida, **b** Ottawa National Forest, **c** Medicine Bow-Routt National Forest, and **d** Plumas National Forest by type of disturbance, based on the ForCaMF model

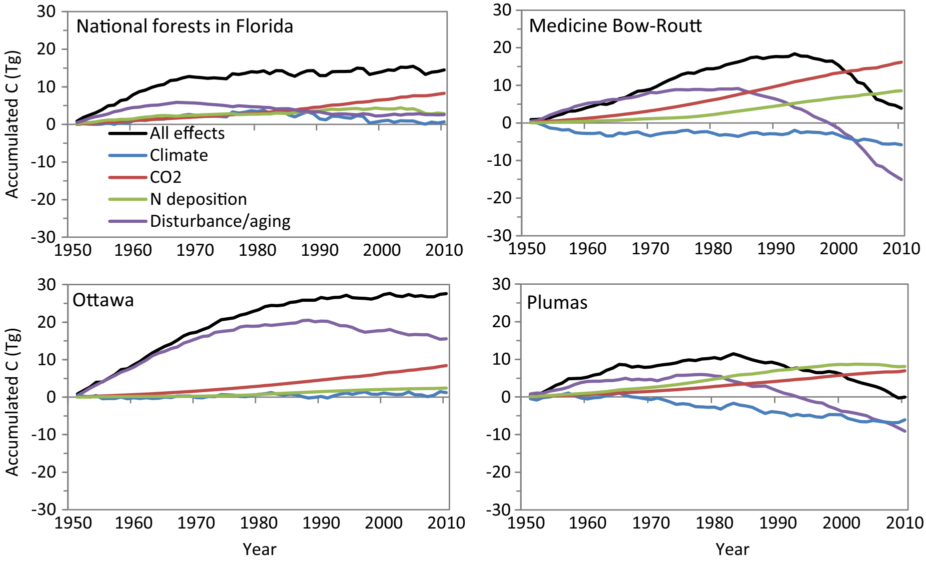

Fig. 5 Accumulated carbon, calculated by consecutively summing the annual C stock changes due to disturbance\aging and non-disturbance factors and all factors combined from 1950 to 2010 excluding C-accumulated pre-1950 for National Forests in Florida and Ottawa, Medicine Bow-Routt, and Plumas National Forests

3.2 Climate and atmospheric effects

Precipitation and temperature had high interannual variability across all four forests, and there are distinct climate-driven trends in a few forests (Fig. S8). For example, temperatures were increasing from 1950 to 2010 in MBR and PNF, which was correlated with a decline in C accumulation (Fig. 5). There are no obvious trends in temperatures in ONF and NFF, which may have led to minor C accumulation in these sites (Fig. 5). The effect of precipitation on C trends is less obvious and may be interacting with temperature changes, but we did not explore this in the model runs.

N deposition increased from the 1950s to the 1990s then declined in the 2000s, while atmospheric CO_2 concentrations steadily increased from 1950 to 2010 across all forests. Both N deposition and increasing CO_2 can enhance growth and productivity and have caused persistent increases in C accumulation across all four forests according to InTEC results (Fig. 5). In MBR and PNF, positive effects of N deposition and CO_2 fully offset C losses due to climate and disturbance/aging, such that MBR experienced a net gain of roughly 4 Tg C from 1950 to 2010, while Plumas saw no net change (Fig. 5). Despite high levels in ONF, N deposition only had a relatively small positive effect on C accumulation.

4 Discussion

4.1 Carbon stock changes in selected US National Forests

Results here and from other studies from North American (e.g., Stinson et al. 2011; Wear and Coulston 2015) and Europe (e.g., Nabuurs et al. 2007) suggest that historical disturbance legacies have significant and lasting effects on forest age structure, C stocks and stock change. Stand age distributions for all four forests show distinct cohorts of stand establishment in the late 1800s through early to mid-1900s (Fig. 2) after disturbances associated with Euro-American settlement such as clearing of land for development or livestock grazing, timber harvest, or major fires. In the eastern sites, extensive regeneration followed federal acquisition of heavily cut-over lands from private owners beginning around 1911 (USDA Forest Service 1939). Policies of fire suppression and forest restoration during the twentieth century enabled newly established stands to survive, while their productivity continued to increase into the mid-1900s, causing C stocks to increase as indicated by InTEC (Fig. 5) and historical inventory data (Birdsey et al. 2006).

After the mid-1900s, forest C stocks continued to increase, a trend revealed by previous studies (Birdsey et al. 2006; Heath et al. 2011b; King et al. 2015). However, effects of different drivers are changing. Older forests have reached a slower growth stage, while newly established stands are reaching peak growth rates but are not as prevalent as older stands. Some areas particularly in the Western USA that are recently subject to more intense disturbances and drought have transitioned from C sinks to sources causing a decline in accumulated C (e.g., Zhang et al. 2012; Wolf et al. 2016).

There is growing evidence that climate change is increasing frequencies and intensities of droughts (Allen et al. 2010), biotic disturbances (Hicke et al. 2016), and fires (Westerling et al. 2006) across the USA and globally. The Landsat-based disturbance records for the four case studies support this, as the forested area affected by disturbances sharply increased starting in the late 1990s (Fig. 3). In some regions such as NFF, elevated post-disturbance regrowth in the 1970s–1990s has counteracted aging-induced declines in C accumulation. Likewise, despite recent declining C stocks (Fig. 5) and lost C storage potential as a result of larger, higher-intensity fires (Fig. 4), the C sink in PNF may rebound in coming years because of regrowth (Fig. 2). As long as forests can recover from widespread and intense disturbances as they have in the past, the strength of the C sink may be maintained or even increase. However, forest recovery after disturbances may be hampered under novel climate conditions characterized by warming temperatures and persistent droughts in some regions (van Mantgem et al. 2009; Allen et al. 2010; Brzostek et al. 2014). This may be a particular risk following high-intensity fires (Savage and Mast 2005). In both western forests, results suggest that warming temperatures were correlated to declines in C accumulation (Fig. 5; Fig. S8). Warmer temperatures increase evaporative demands and water deficits leading to heightened tree mortality (van Mantgem et al. 2009). Elevated temperatures also increase decomposition rates and respiration particularly in more northern regions (e.g., Davidson and Janssens 2006).

Model results here and from other studies (Forkel et al. 2016) indicate the important role of atmospheric composition on forest C stocks. In forests examined here, growth enhancements due to N deposition and CO_2 fertilization have partially offset recent losses due to disturbance and climate (Fig. 5). However, in some cases, particularly in the Northeastern USA, chronically elevated levels of N deposition may lead to N saturation, nitrate leaching, and increased tree mortality (Aber et al. 1998; Magill et al. 2004). In western US forests which are more nutrient limited, in the absence of N deposition and CO_2 fertilization, forests would have experienced net C losses compared with 1950. The additive effects of increasing N deposition and CO_2 on C accumulation may be significantly stronger over the long term than the effects of climate variability (Pan et al. 2009; Zhang et al. 2012).

4.2 Integrating information for forest carbon assessment

This study demonstrates how remote sensing and field observations coupled with empirical and process-based models enable comprehensive assessment of effects of natural disturbances, land management, and environmental factors on forest C stocks and trends. Until recently, detailed analyses could not be practically undertaken with this level of consistency across the USA. Parallel advances in interpreted satellite data, ecosystem modeling, forest inventory, understanding of disturbance impacts, and the ability to integrate this information are making such analyses more feasible (Masek et al. 2015), extending the capacity for assessing forest sector climate mitigation opportunities (Birdsey et al. 2013).

Remotely sensed Landsat data provide nearly 30 years of continuous land cover change monitoring. Recent advances in processing this vast data archive (Masek et al. 2013) and attributing changes to specific causes (Mascorro et al. 2015) have facilitated preparation of detailed disturbance histories and impacts on C stocks for most regions of the world. Improved spatial accuracy is important for better integration of remote sensing records with other data (Healey et al. 2014).

Identifying long-term impacts of various disturbance types and intensities on forest C pools is critical for tracking CO_2 emissions over time because disturbances redistribute C among different pools with highly variable residence times (McKinley et al. 2011). Rates of transfer between pools depend on disturbance types and intensities, forest type, geographic location, and biomass density; models quantifying transfer rates have been estimated here for all regions of the conterminous USA using FVS (Raymond et al. 2015). The library of regionally averaged C transfer rates may be useful in forest planning applications and environmental assessments to estimate impacts of individual management activities on C stocks.

FIA's baseline data represent both a credible estimate of trends in C stocks and observed data points for model calibration (Birdsey et al. 2013). However, FIA's relatively sparse sample of plots remeasured every 5–10 years, does not reflect fine-scale, interannual variability and delays detection of disturbances that may affect C stocks. These limitations of the FIA data and CCT model were evident in results from the two western forests, which showed increases in C density (Fig. S7) despite significant insect and fire disturbances detected by the Landsat imagery (Fig. 4). In contrast, ForCaMF and InTEC which utilize Landsat observations captured the C declines due to these recent disturbance events (Fig. 5). Supplementing FIA data with more contemporary Landsat observations within ForCaMF and InTEC may better capture the temporal dynamics of forests and C stock changes.

Although InTEC and ForCaMF evaluate effects of various disturbance and management types on C stocks, there are several key differences between these models to consider when making direct comparisons. ForCaMF models the effects of disturbance and management on non-soil C stocks, while InTEC tracks soil C transfers (see ESM 1). This is a significant difference as soil C is one of the largest C pools in forest ecosystems (e.g., Scharlemann et al. 2014). Additionally, ForCaMF primarily tracks potential lost C storage by estimating how much more C would be on a landscape if individual disturbances had not occurred (Healey et al. 2016), whereas InTEC reports C stock changes and accumulations due to all disturbance types and aging effects combined.

Model results also vary due to inherent differences in modeling approaches. For instance, CCT relies on allometric models of volume, species, and tree dimensions to convert tree measurements to biomass and carbon (Woodall et al. 2011a). Similarly, ForCaMF uses individual tree measurements and site characteristics within FVS to simulate C stocks and trends. InTEC is fundamentally different as a hybrid empirical/process model, driven by biogeochemical processes such as C assimilation and N mineralization (e.g., Zhang et al. 2012) and does not rely on biometrics. These distinctions in modeling techniques likely cause some discrepancies in results.

The forest area in each National Forest may differ by model. CCT uses the FIA definition of forest in which a forest land has at least 36.6 m (120 ft) wide and 0.4 ha (1 acre) in size and with at least 10% cover (or equivalent stocking) by live trees, including land that formerly had such tree cover and can be naturally or artificially regenerated (Bechtold and Patterson 2005). Thus, forest area can change over survey years given land use or administrative boundary changes, although changes in FIA sampling design and definitions in the late 1990s have introduced some discontinuity in total forest land area and consequently C estimates over time (Woodall et al. 2011a; Goeking 2015). Conversely, InTEC employs a single forest-type map based in part on FIA data (Ruefenacht et al. 2008), thus assumes a constant forest area over the study period. While effects of forest land definitions on forest C estimates have not been evaluated, it is important to be aware that model results for individual forests may differ, sometimes considerably, for a variety of reasons.

Integrating different datasets and model results into a cohesive and credible description of observed trends has been the main challenge in this study. In the end, we have tried to ensure that results from data analyses and models are consistent with the observations by land managers who are very familiar with these ecosystems and with available historical references about land management and disturbance events.

4.3 Uncertainty and research needs

There are uncertainties in both input datasets and model results, and these uncertainties can be difficult to quantify (e.g., Heath et al. 2011b). For example, uncertainties with observation-based data may include human sampling errors, though these are reduced by exhaustive quality control and assurance measures (Bechtold and Patterson 2005). InTEC relies on FIA stand-age data; however, in multi-aged plots, variable stand ages are averaged to obtain a single representative age for mapping age polygons (see ESM 1). Multi-aged areas may not behave in the same way as their truly even-aged counterparts, whereas stand metrics like relative density might be more meaningful in terms of C accumulation in these situations (Woodall et al. 2011b). Additionally, despite supplementing FIA data with high-resolution Landsat disturbance data, small (<30 m) and/or very low-severity disturbances may still go undetected. Also, although the spatially continuous and contemporary nature of Landsat data enables a robust assessment of disturbances, forest canopy disturbances can sometimes be misinterpreted as land-use change rather than forest management activities (Woodall et al. 2016). Land-use change was not evaluated in this study since the National Forest land base is fairly static compared with private lands. Furthermore, some model parameters were derived from observations of limited extent or from analysis of empirical data such as those performed using FVS, especially those that represent key processes like respiration and temperature sensitivity.

To evaluate uncertainty in model inputs and results, CCT employs a Monte-Carlo approach in which model simulations are repeated 2000 times until uncertainty estimates stabilize (Woodall et al. 2011a). Similarly, ForCaMF uses a generalized uncertainty framework called “PDF Weaving” that integrates FIA sampling uncertainty, remote sensing error, and modeling error (Healey et al. 2014). Uncertainty analyses are often not conducted for process-based models, although they are known to have considerable uncertainty due to incomplete understanding of mechanisms underlying ecosystem processes and inherent uncertainty in parameter values used to represent processes (Zaehle et al. 2005). Different process models using the same input datasets typically have significantly different results (e.g., Schaefer et al. 2012). However, sensitivity analyses of InTEC inputs and assumptions and calibration with multiple observational datasets indicates that modeled results produce a reasonable range for the total effect of all factors on forest C comparable with empirical model results, though the partitioning of factorial effects may be less certain (Zhang et al. 2012, 2015).

4.4 Management implications

National Forests tend to have higher C densities than private forests generally and in more contiguous landscapes (Heath et al. 2011a). Furthermore, goals for land management are driven by quite different uses and decision-making processes (Dilling et al. 2013). Understanding effects of management decisions on current and future C stocks is increasingly becoming a requirement (e.g., USDA Forest Service 2010) though managing forest C stocks may not be mandated. Forest management strategies that seek accretion of C stocks must also address impacts on other management objectives and related ecosystem services.

We have taken a multi-modal approach to understanding and differentiating relative impacts of factors including management, natural disturbance, atmospheric change, and climatic variation on C storage. While results presented here point to national trends in the impact of both disturbance and climate in forest C storage, the primary benefit from a manager's point of view is that results apply to relatively local landscape scales at which policies and management strategies are implemented. These assessments form the best-available nationally consistent foundation for making informed management decisions about maintaining or enhancing C storage in the context of other priorities for public lands.

Acknowledgments This research was supported by US Forest Service and NASA grants and is built on research supported by these two agencies over the last decade or so. We acknowledge the many US Forest Service managers, planners, and ecologists who have raised questions and offered constructive suggestions about interpreting and presenting results of this work to public land managers.

References

Aber J, McDowell W, Nadelhoffer K, Magill A, Berntson G, Kamakea M, McNulty S, Currie W, Rustad L, Fernandez I (1998) Nitrogen saturation in temperate forest ecosystems. Bioscience 48:921–934

Allen CD, Macalady AK, Chenchouni H, Bachelet D, McDowell N, Vennetier M et al (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manag 259:660–684

Bechtold WA, Patterson PL (2005) The enhanced forest inventory and analysis program—national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. US Department of Agriculture Forest Service, Southern Research Station, Asheville, NC 85 p

Bellasson V, Viovy N, Luyssaert S, Le Maire G, Schelhaas M-J, Ciais P (2011) Reconstruction and attribution of the carbon sink of European forests between 1950 and 2000. Glob Chang Biol 17:3274–3292

Birdsey R, Pregitzer K, Lucier A (2006) Forest carbon management in the United States: 1600–2100. J Environ Qual 35:1461–1469

Birdsey R, Angeles-Perez G, Kurz WA, Lister A, Olguin M, Pan Y, Wayson C, Wilson B, Johnson K (2013) Approaches to monitoring changes in carbon stocks for REDD+. Carbon Management 4:519–537

Brzostek ER, Dragoni D, Schmid HP, Rahman AF, Sims D, Wayson CA, Johnson DJ, Phillips RP (2014) Chronic water stress reduces tree growth and the carbon sink of deciduous hardwood forests. Glob Chang Biol 20:2531–2539

Crookston NL, Dixon GE (2005) The forest vegetation simulator: a review of its structure, content, and applications. Comput Electron Agric 49:60–80
Davidson EA, Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440:165–173
Dilling L, Birdsey R, Pan Y (2013) Opportunities and challenges for carbon management on U.S. public lands. Chapter 18. In: Brown, DG, Robinson, DT French, NHF, Reed, BC, eds. Land use and the carbon cycle: advances in integrated science, management and policy. Cambridge, UK: Cambridge Press. 455–476
Eidenshink J, Schwind B, Brewer K, Zhu Z, Quayle B, Howard S (2007) A project for monitoring trends in burn severity. Fire Ecology 3:3–21
Fang J, Kato T, Guo Z, Yang Y, Hu H, Shen H, Zhao X, Kishimoto-Mo AW, Tang Y, Houghton RA (2014) Evidence for environmentally enhanced forest growth. Proc Natl Acad Sci 111:9527–9532
Forkel M, Carvalhais N, Rödenbeck C, Keeling R, Heimann M, Thonicke K, Zaehle S, Reichstein M (2016) Enhanced seasonal CO2 exchange caused by amplified plant productivity in northern ecosystems. Science 351:696–699
Goeking SA (2015) Disentangling forest change from forest inventory change: a case study from the US interior west. J For 113:475–483
He L, Chen JM, Pan Y, Birdsey RA (2012) Relationships between net primary productivity and Forest stand age derived from forest inventory and analysis data and remote sensing imagery. Glob Biogeochem Cycles 26: GB3009. doi:10.1029/2010GB003942
Heath LS, Smith JE, Woodall CW, Azuma DL, Waddell KL (2011b) Carbon stocks on forestland of the United States, with emphasis on USDA Forest Service ownership. Ecosphere 2(1) article 6
Heath LS, Smith JE, Skog KE, Nowak DJ, Woodall CW (2011a) Managed forest carbon estimates for the US greenhouse gas inventory, 1990-2008. J For 109:167–173
Healey SP, Urbanski SP, Patterson PL, Garrard C (2014) A framework for simulating map error in ecosystem models. Remote Sens Environ 150:207–217
Healey SP, Raymond CL, Lockman IB, Hernandez AJ, Garrard C, Huang C (2016). Root disease can rival fire and harvest in reducing forest carbon storage. Ecosphere
Hicke JA, Meddens AJH, Kolden CA (2016) Recent tree mortality in the Western United States from bark beetles and forest fires. For Sci 62:141–153
Huang C, Goward SN, Masek JG, Thomas N, Zhu Z, Vogelmann JE (2010) An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks. Remote Sens Environ 114:183–198
Johnson EW, Wittwer D (2008) Aerial detection surveys in the United States. Aust For 71:212–215
King AW, Andres RJ, Davis KJ, Hafer M, Hayes DJ, Huntzinger DN, de Jong B, Kurz WA, McGuire AD, Vargas R, Wei Y, West TO, Woodall CW (2015) North America's net terrestrial CO2 exchange with the atmosphere 1990-2009. Biogeosciences 12:399–414
Law BE, Turner D, Campbell J, Van Tuyl S, Ritts WD, Cohen WB (2004) Disturbance and climate effects on carbon stocks and fluxes across Western Oregon USA. Glob Chang Biol 10:1429–1444
Magill AH, Aber JD, Currie WS, Nadelhoffer KJ, Martin ME, McDowell WH, Melillo JM, Steudler P (2004) Ecosystem response to 15 years of chronic nitrogen additions at the Harvard Forest LTER, Massachusetts, USA. For Ecol Manag 196:7–28
Mascorro VS, Coops NC, Kurz WA, Olguín M (2015) Choice of satellite imagery and attribution of changes to disturbance type strongly affects forest carbon balance estimates. Carbon Balance Management 10:30
Masek JG, Hayes DJ, Hughes MJ, Healey SP, Turner DP (2015) The role of remote sensing in process-scaling studies of managed forest ecosystems. For Ecol Manag 355:109–123
Masek JG, Goward SN, Kennedy RE, Cohen WB, Moisen GG, Schleeweis K, Huang C (2013) United States forest disturbance trends observed using Landsat time series. Ecosystems 16:1087–1104
McKinley DC, Ryan MG, Birdsey RA, Giardina CP, Harmon ME, Heath LS, Houghton RA, Jackson RB, Morrison JF, Murray BC, Pataki DE, Skog KE (2011) A synthesis of current knowledge on forests and carbon storage in the United States. Ecol Appl 21:1902–1924
Nabuurs GJ, Masera O, Andrasko K, Benitez-Ponce P, Boer R, Dutschke M, Elsiddig E, Ford-Robertson J, Frumhoff P, Karjalainen T, Krankina O, Kurz WA, Matsumoto M, Oyhantcabal W, Ravindranath NH, Sanz Sanchez MJ and Zhang X (2007) Forestry. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate change 2007: mitigation. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, New York
Pan Y, Birdsey R, Hom J, McCullough K (2009) Separating effects of changes in atmospheric composition, climate and land-use on carbon sequestration of U.S. mid-Atlantic temperate forests. For Ecol Manag 259:151–164
Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala SW, McGuire AD, Piao S, Rautiainen A, Sitch S, Hayes D (2011) A large and persistent carbon sink in the World's forests. Science 333:988–993

Perez-Garcia J, Lippke B, Comnick J, Manriquez C (2005) An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. Wood Fiber Sci 37:140–148
Raymond CL, Healey S, Peduzzi A, Patterson P (2015) Representative regional models of post-disturbance forest carbon accumulation: integrating inventory data and a growth and yield model. For Ecol Manag 336:21–34
Ruefenacht B, Finco MV, Nelson MD, Czaplewski R, Helmer EH, Blackard JA, Holden GR, Lister AJ, Salajanu D, Weyermann D, Winterberger K (2008) Conterminous US and Alaska forest type mapping using forest inventory and analysis data. Photogramm Eng Remote Sens 74:1379–1388
Sample VA, O'Malley R, Kittler B (2010) Forest sustainability in the development of wood bioenergy. Pinchot Institute, Washington, DC
Savage M, Mast JN (2005) How resilient are southwestern ponderosa pine forests after crown fire? Can J For Res 35:967–977
Schaefer K et al (2012) A model-data comparison of gross primary productivity: results from the North American carbon program site synthesis. J Geophys Res 117:G03010
Scharlemann JPW, Tanner EVJ, Hiederer R, Kapos V (2014) Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Management 5:81–91
Smith JE, Heath LS, Nichols MC (2010) US Forest carbon calculation tool: forest-land carbon stocks and net annual stock change. Revised. Gen. Tech. Rep. NRS-13. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newtown Square, PA 34 p
Stinson G, Kurz WA, Smyth CE, Neilson ET, Dymond CC, Metsaranta JM et al (2011) An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. Glob Chang Biol 17:2227–2244
Stockmann KD, Anderson NM, Skog KE, Healey SP, Loeffler DR, Jones G, Morrison JF (2012) Estimates of carbon stored in harvested wood products from the United States Forest Service northern region, 1906-2010. Carbon Balance and Management 7:1–16
Ter-Mikaelian MT, Colombo SJ, Chen J (2015) The burning question: does forest bioenergy reduce carbon emissions? A review of common misconceptions about Forest carbon accounting. J For 113:57–68
UNFCCC (2015) Adoption of the Paris Agreement FCCC/CP/2015/L.9/Rev.1. United Nations Framework Convention on Climate Change, 21st Conference of the Parties, Geneva, Switzerland: United Nations Office
USDA Forest Service (1939) Florida National Forests. Washington, D.C, United States Government Printing Office
USDA Forest Service (2010) A performance scorecard for implementing the Forest Service Climate Change Strategy
US Department of State (2015) U.S. government and companies reiterate commitment to Forest and climate programs. US Department of State, Washington, DC
USEPA (2015) Inventory of US greenhouse gas emissions and sinks: 1990–2013. US Environmental Protection Agency, Washington, D.C.
van Mantgem PJ, Stephenson NL, Byrne JC, Daniels LD, Franklin JF, Fulé PZ et al (2009) Widespread increase of tree mortality rates in the western United States. Science 323:521–524
Wear D, Coulston J (2015) From sink to source: regional variation in U.S. forest carbon futures. Nature. Scientific Reports 5, Article number: 16518
Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western U.S. Forest wildfire activity. Science 313:940–943
Wolf S, Keenan TF, Fisher JB, Baldocchi DD, Desai AR, Richardson AD, Scott RL, Law BE, Litvak ME, Brunsell NA, Peters W, van der Laan-Luijkx IT (2016) Warm spring reduced carbon cycle impact of the 2012 US summer drought. PNAS 113:5880–5885
Woodall CW, D'Amato AW, Bradford JB, Finley AO (2011a) Effects of stand and inter-specific stocking on maximizing standing tree carbon stocks in the eastern USA. For Sci 57:365–378
Woodall CW, Heath LS, Domke GM, Nichols MC (2011b) Methods and equations for estimating aboveground volume, biomass, and carbon for trees in the U.S. forest inventory, 2010. Gen. Tech. Rep. NRS-88. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 30 p
Woodall CW, Walters BF, Coulston JW, D'Amato AW, Domke GM, Russell MB, Sowers PA (2016) A tale of two forest carbon assessments in the eastern United States: forest use versus cover as a metric of change. Ecosystems 19:1401–1417
Zaehle S, Sitch S, Smith B, Hatterman F (2005) Effects of parameter uncertainties on the modeling of terrestrial biosphere dynamics. Glob Biogeochem Cycles 19:GB3020
Zhang F, Chen JM, Pan Y, Birdsey R, Shen S, Ju W, Dugan AJ (2015) Impacts of inadequate historical disturbance data in the 20th century on modeling recent carbon dynamics (1951-2010) in conterminous US forests. Journal of Geophysical Research: Biogeosciences 120:549–569
Zhang FM, Chen JM, Pan Y, Birdsey RA, Shen S, Ju W, He L (2012) Attributing carbon changes in conterminous U.S. forests to disturbance and non-disturbance factors from 1901-2010. J Geophys Res 117:G02021