UTILIZING FOREST INVENTORY AND ANALYSIS DATA, REMOTE SENSING, AND ECOSYSTEM MODELS FOR NATIONAL FOREST SYSTEM CARBON ASSESSMENTS

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Abstract—Forested lands, representing the largest terrestrial carbon sink in the United States, offset 16% of total U.S. carbon dioxide emissions through carbon sequestration. Meanwhile, this carbon sink is threatened by deforestation, climate change and natural disturbances. As a result, U.S. Forest Service policies require that National Forests assess baseline carbon stocks and influences of disturbance and management activities on carbon stocks and trends, with the goal of incorporating carbon stewardship into management activities. To accomplish these objectives, we utilize Forest Inventory and Analysis datasets and remote sensing-based disturbance histories within a carbon modeling framework to estimate past and present carbon stocks and trends for each national forest. We integrate three forest carbon models: 1) Carbon Calculation Tool, 2) Forest Carbon Management Framework, and 3) Integrated Terrestrial Ecosystem Carbon model, to calculate baseline carbon stocks and the relative impacts of disturbance and non-disturbance factors on forest carbon stocks and flux. Results of the assessments ultimately help forest managers quantify carbon consequences of broad forest management strategies and project-level decisions. A case study from Flathead National Forest shows that disturbances, primarily fire and disease, have had the largest effect on forest carbon stocks.

INTRODUCTION

Containing approximately a quarter of the total carbon (C) stored in U.S. forests, the National Forest System can play a critical role in mitigating greenhouse gas emissions through C sequestration. Climate change along with natural and anthropogenic disturbances may threaten or in some cases enhance forest C stocks. The effects of climate change and disturbances on forest C are both spatially and temporally complex, further complicating forest C management. Few studies have examined in detail the drivers of C stocks and trends at landscape-management scales, such as across individual National Forests. Forest C assessments including a full attribution of natural and anthropogenic causes of observed change at the scale at which management decisions are made are needed.

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Recognizing this, both international and national policies have been enacted with the goal of managing and sustaining these valuable forest resources. By signing the United National Framework Convention on Climate Change (UNFCCC), the U.S. agreed to report annual C stores and changes, including those on forested lands, as part of a complete greenhouse gas inventory. Furthermore, the U.S. Forest Service Climate Change Response Strategy and Performance Scorecard requires management units (i.e., National Forests) to report baseline C stocks and changes over time due to disturbance and management, and in the future, it is likely that management guidelines will incorporate C stewardship among other objectives.

To address these mandates, we integrated remotely sensed and field-sampled data sources within a C modeling framework to develop a comprehensive assessment of forest C stocks and dynamics within each U.S. National Forest. Specifically we estimated the following: 1) baseline C stocks via the Carbon Calculation Tool (CCT), 2) effects of disturbances on C accumulation using the Forest Carbon Management Framework (ForCaMF), and 3) long-term relative effects of disturbance and non-disturbance factors (climate and atmospheric chemistry) on C stocks and flux using the Integrated Terrestrial Ecosystem Carbon model (InTEC).

DATA SOURCES

Fundamental to the assessment of forest C stocks is a thorough inventory of all forested lands. The U.S. Forest Inventory and Analysis (FIA) program provides a nationally-consistent and statistically-valid sample documenting trends in forest extent, status, condition, and resources. Within each FIA plot, variables useful to C accounting are collected such as forest type, tree species, tree size, stand age, and recent disturbances (Bechtold and Patterson 2005). FIA datasets can be utilized to directly calculate tree volume, biomass, and C stocks via allometric equations (e.g., Woodall and others 2011). Along with FIA forested area measurements, C density and total C stocks in component pools can be estimated for an area of interest, such as a National Forest (e.g., Woodall and others 2013). FIA data is also suitable for deriving other C modeling inputs such as stand age and forest type maps (Zhang and others 2012), and growth and yield functions (Raymond and others 2015). Utilizing inventory-based, on-the-ground measurements enhances model confidence and facilitates comparisons across forests.

Along with other forest characteristics, disturbances, including their timing, types, and magnitudes, regulate the amount of C present in a forest and how that C may fluctuate overtime. Although inventory data is useful for tracking total C and net changes, and can reveal the effects of harvesting and mortality, it is less suited for tracking effects of specific disturbances and intensities on C stocks, and cannot assess the impact of climate change and atmospheric chemistry. Therefore, high-resolution disturbance and atmospheric data is also needed to model C dynamics with attribution to specific causes of change. Landsat satellite imagery and manual verification are used to detect annual changes in forest cover, and assign disturbance types (e.g., fire, insect, harvest) and magnitudes at 30-m resolution from 1990-2011 (Healey and others 2014). High-resolution, measurement-based datasets (e.g. PRISM Climate Group) enable us to investigate growth enhancements and reductions due to climatic variability, CO_2 fertilization, and nitrogen deposition.

MODELING FRAMEWORK

For this project we use CCT (Smith and others 2010) to provide baseline C stocks and trends from 1990-2013 on forested lands in National Forests. Annual C stocks are calculated by linear interpolation between at least two complete FIA surveys conducted since 1990, and extrapolation to recent years after the last available inventory. C stocks within FIA plots are calculated using regional and forest-type specific conversion factors and coefficients within sets of equations (e.g., Woodall and others 2011). To estimate total C for each national forest, the C per hectare at the plot location is multiplied by the total area that the plot represents, and then these totals are summed. CCT accounts for changes in forest area reflected in the FIA data, thus also reports annual C density (Woodall and others 2013).

ForCaMF builds upon CCT by utilizing FIA data along with Landsat-derived disturbance histories to estimate the relative impacts of disturbances and management activities on C stored in forested ecosystems from 1990-2011 (Healey and others 2014). FIA plots are used as inputs to the Forest Vegetation Simulator (FVS) model (Crookston and Dixon 2005) to simulate C trajectories for non-soil C pools in 10-year intervals over a 100-year span (Raymond and others 2014). These trajectories are then used to track C storage change on the national forest over time as they are applied across Landsat-based maps of forest structure and disturbance. The relative impacts of disturbances are quantified based on the direct export of C to the atmosphere or other pools and prevented sequestration (Healey and others 2014, Raymond and others 2015).

Lastly, InTEC (Chen and others 2000, Zhang and others 2012) expands upon both CCT and ForCaMF by attributing C stocks and flux to non-disturbance and disturbance factors. InTEC is a process-based, biogeochemical model calibrated with FIA-derived inputs including stand age, forest type, and net primary productivity-stand age relationships that drive forest growth (Zhang and others 2012). InTEC estimates the impacts of Landsat disturbances and stand age (time-since-disturbance) by calculating C emissions, transfers between live and dead pools, and accumulation. Fluctuations in non-disturbance factors including climate (i.e., temperature, precipitation), nitrogen deposition and atmospheric CO_2 concentrations, which influence growth rates, guide forest C dynamics. A series of differential equations along with scalars and coefficients of allocation, turnover, decomposition, and C loss controls how disturbance and non-disturbance factors affect total net biome productivity and component C pools since 1950.

RESULTS AND DISCUSSION

A Case Study: Flathead National Forest

Flathead National Forest (FNF) in Northwestern Montana, contains predominately subalpine fir (*Abies lasiocarpa*) and Douglas fir (*Pseudotsuga menziesii*) forests and about 10% of the forests are <10 years old (Fig. 1). Results of CCT in FNF indicate that from 1990-2013 C density remained relatively stable around 155 Mg ha^{-1} C (Fig. 2a), with aboveground live tree and soil C pools containing most forest C (Fig. 2b). ForCaMF results show that since 1990, there has been an increase in disturbance effects, with disease and fire having the greatest relative impacts (Fig. 3a). By 2011, disturbances emitted or prevented the sequestration of 4.8 Tg C, with considerable emissions in 2004 and 2007 due to fires (Fig. 3a). Increased disturbances may explain the subtle decline in C density in aboveground and belowground live pools and subsequent increase in dead down, standing dead, and forest floor pools from 1990-2013 (Fig. 2b). InTEC outputs reveal that since the 1950s FNF fluctuated between a small C sink and source, but from 2000-2009 it remained a C source (Fig. 3b) due to both negative disturbance/aging and climatic effects (i.e., warmer, drier) (Figs. 3c-d). In 2010 FNF became a C sink again (Figs. 2b-c) as forests began recovering from recent disturbances (Fig. 3a) shown by the pulse of newly established stands (Fig. 1). The positive impacts of nitrogen deposition and CO_2 fertilization were generally overshadowed by the much stronger, mostly negative disturbance and climate effects, cumulatively causing a loss in C over time (Figs. 3b-d).

These C assessments can help inform management decisions. Results from FNF suggest that despite increased disturbances, C density has been stable (Fig. 1a). However, if the goal is to increase C storage, it may be most effective to focus on mitigating disturbance effects, specifically disease and fire, which have had the most negative impacts on C trends (Fig. 2a). It is important that national forest managers place C management within a broader context of long-term sustainable management. These forests are diverse, multi-use landscapes and C management adds another very complex dimension to already complicated strategies.

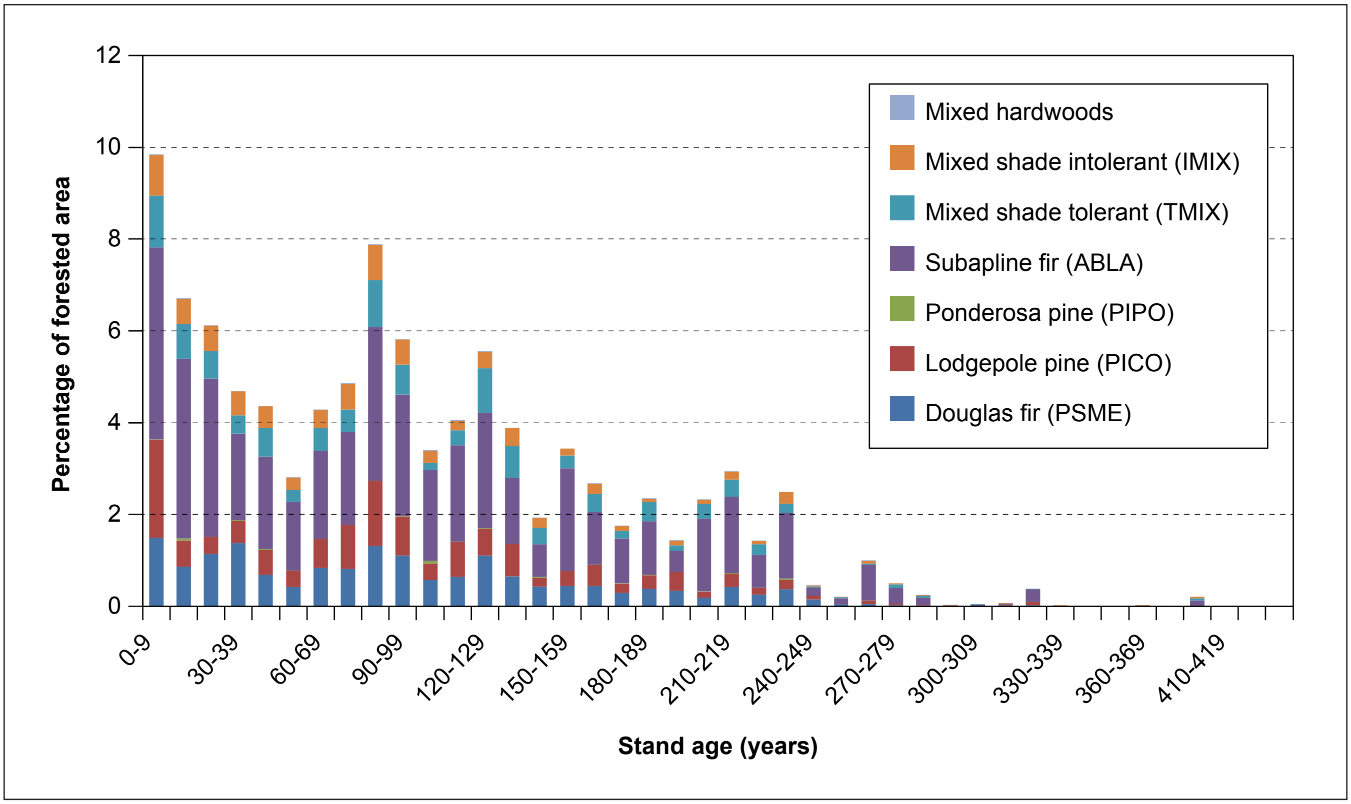

Figure 1—Age-class distribution displaying the percentage of forested area of each forest dominance type in 10-year age classes, derived from Forest Inventory and Analysis data.

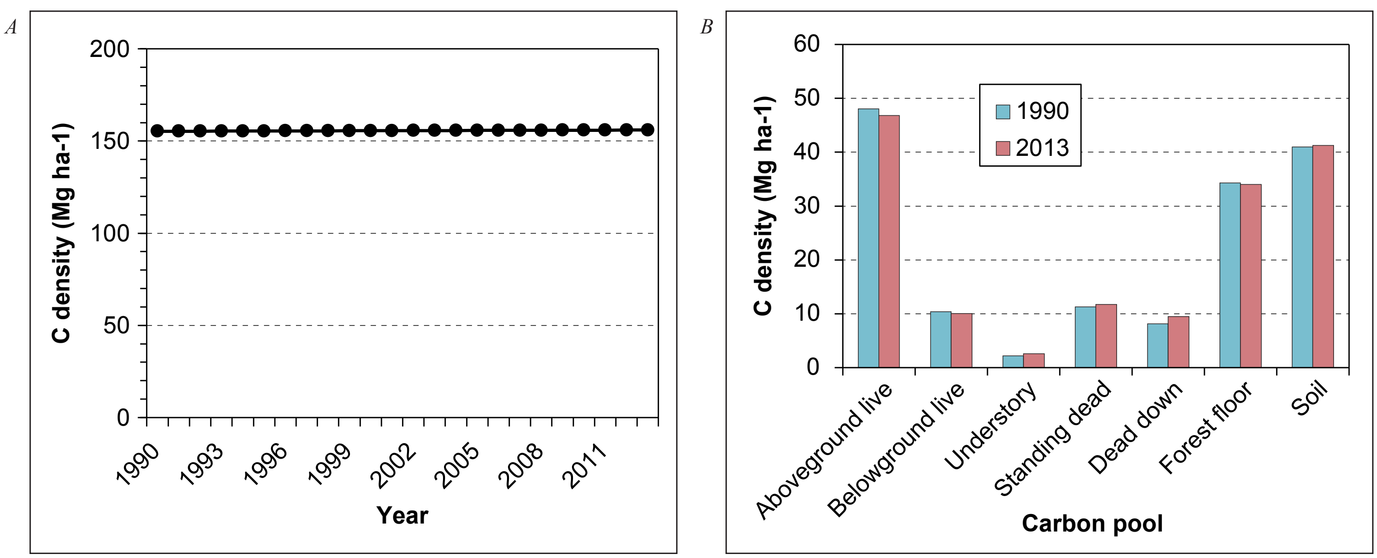

Figure 2—Carbon Calculation Tool outputs for Flathead National Forest showing carbon density (Mg C ha-1) for (a) all ecosystem carbon pools combined from 1990-2013 and (b) each individual carbon pool in 1990 and 2013.

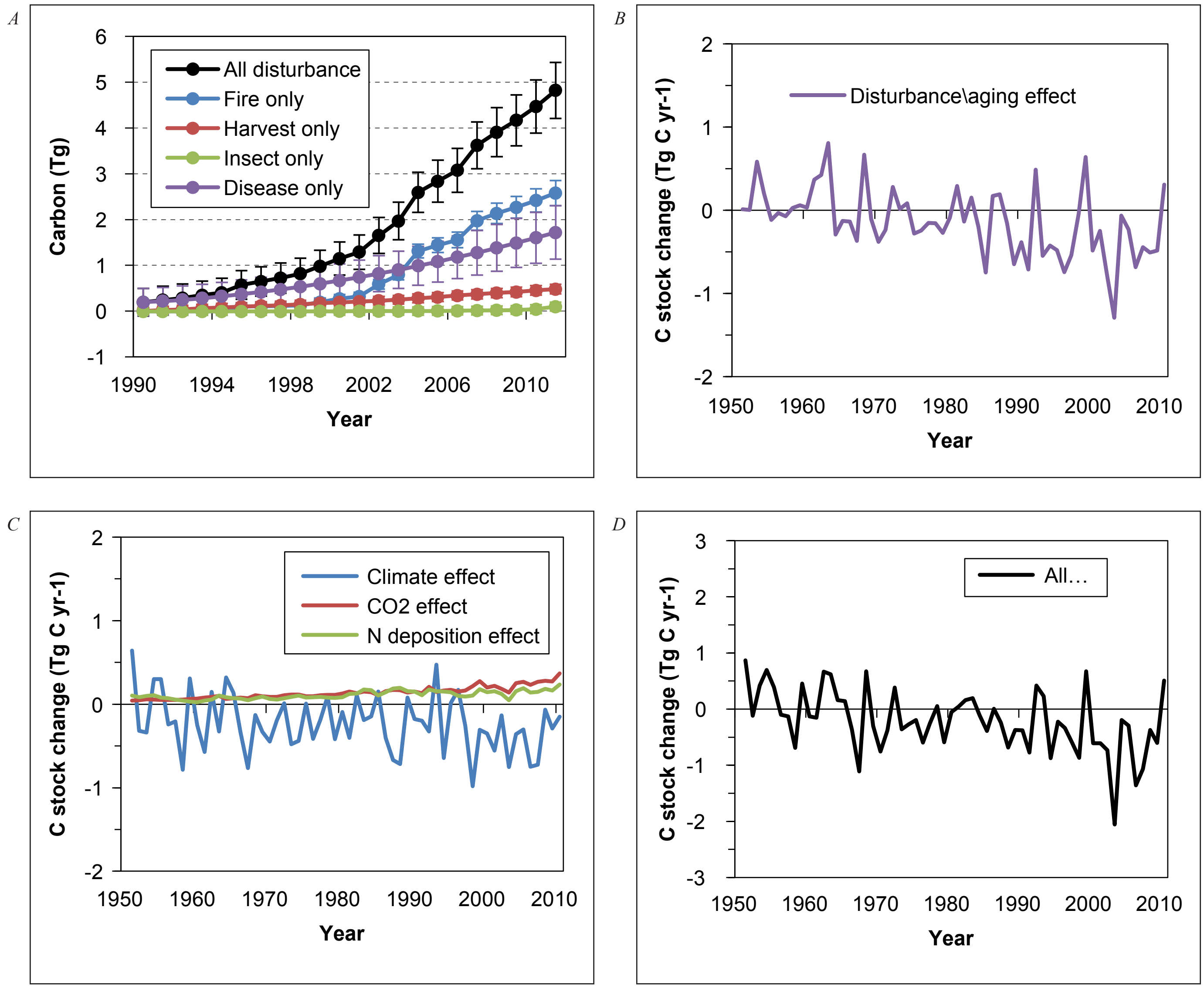

Figure 3—Model outputs for Flathead National Forest showing the relative effects of disturbance and non-disturbance factors on forest carbon trends. (a) Output from the Forest Carbon Management Framework showing impacts of management and disturbances occuring from 1990 and 2011 on non-soil C storage. Error bars specify the standard error of 500 error simulations. InTEC outputs showing the changes in total ecosystem C stocks from 1951-2010 due to: (b) disturbances including fire, harvests, insects, and disease and subsequent regrowth with stand age, (c) non-disturbance factors including climatic variability, nitrogen deposition, and atmospheric CO2 concentrations, and (d) all disturbance/aging and non-disturbance factors combined. Positive values indicate the forest is a C sink from the atmosphere whereas negative values indicates a C source to the atmosphere.

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