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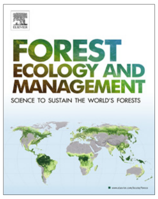

Decadal change of forest biomass carbon stocks and tree demography in the Delaware River Basin

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ABSTRACT

Quantifying forest biomass carbon (C) stock change is important for understanding forest dynamics and their feedbacks with climate change. Forests in the northeastern U.S. have been a net carbon sink in recent decades, but C accumulation in some northern hardwood forests has been halted due to the impact of emerging stresses such as invasive pests, land use change and climate change. The Delaware River Basin (DRB), sited in the southern edge of the northern hardwood forest, features diverse forest types and land-use histories. In 2001–2003, the DRB Monitoring and Research Initiative established 61 forest plots in three research sites, using Forest Service inventory protocols and enhanced measurements. These plots were revisited and re-measured in 2012–2014. By comparing forest biomass C stocks in the two measurements, our results suggest that the biomass C stock of the DRB forest increased, and was thus a carbon sink over the past decade. The net biomass C stock change in the Neversink area in the north of the DRB was 1.94 Mg C ha^{-1} yr^{-1}, smaller than the biomass C change in the French Creek area (2.52 Mg C ha^{-1} yr^{-1}, southern DRB), and Delaware Water Gap Area (2.68 Mg C ha^{-1} yr^{-1}, central DRB). An increase of dead biomass C accounted for 20% of the total biomass C change. The change of biomass C stocks did not correlate with any climatic or topographic factors, but decreased with increasing stand age, and with tree mortality rate. Mortality rates were highest in the smallest size class. In most of the major tree species, stem density decreased, but the loss of biomass from mortality was offset by recruitment and growth. The demographic changes differ dramatically among species. The living biomass of chestnut oak, white oak and black oak decreased because of the large mortality rate, while white pine, American beech and sweet birch increased in both biomass and stem density. Our results suggest that forests in the DRB could continue to be a carbon sink in the coming decades, because they are likely at a middle successional stage. The linkage between demography of individual trees species and biomass C change underscores the effects of species-specific disturbances such as non-native insects and pathogens on forest dynamics, and highlights the need for forest managers to anticipate these effects in their management plans.

1. Introduction

As global forest C stocks have increased consistently in the past several decades, their potential to sequester additional atmospheric carbon dioxide (CO_2) is considered a mitigation strategy to reduce global warming (Luyssaert et al., 2007; Pan et al., 2011; Ciais et al., 2013). Quantifying forest biomass C stock change and identifying the factors causing changes are important to understand forest dynamics and its feedback with climate change, and to successfully implement forest carbon management strategies (Hyvonen et al., 2007; Bonan, 2008). However large uncertainty still exists as forest biomass is highly heterogeneous (both spatially and temporally), and its dynamics are determined by different factors at different scales (Birdsey et al., 2006; Pan et al., 2013).

It is widely accepted that seasonal weather and climate regulate short-term fluctuations of carbon uptake, while disturbance history and management control C stock change on decadal time scales (Barford et al., 2001; Williams et al., 2012). Climatic, topographic and geologic factors determine forest dynamics across a broader range of environmental conditions, while stand age and gap dynamics control biomass accumulation at smaller spatial scales (Brandeis et al., 2009; Yi et al., 2010). Living tree biomass

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is one of the largest and most active C pools in forest ecosystems (Woodbury et al., 2007), and its dynamics are driven by the balance among three forest demographic changes: growth, recruitment and mortality (including harvesting). Each of these demographic changes can vary with age and species (Vanderwel et al., 2013a; Rozendaal and Chazdon, 2015). Long-term, periodic biometric measurements provide a unique opportunity to not only investigate forest biomass C dynamics at the regional scale, but also link biomass C stock with demographic change (Curtis et al., 2002; Xu et al., 2014).

Based on inventory data, forests in the northeastern U.S. are an overall net sink for atmospheric carbon in recent decades (Turner et al., 1995; Lu et al., 2013). However, C accumulation in some northern hardwood forests has been halted due to the impact of emerging stresses such as invasive pests, land use change and climate change (Brooks, 2003; Siccama et al., 2007; Duarte et al., 2013). Small scale disturbances such as invasive pests, disease and selective harvesting may affect species differently, and increase C turnover at regional scales (Makana et al., 2011). The Delaware River Basin (DRB), situated in the southern edge of the northern hardwood forest, features diverse forest types and land-use histories. Most of the forests in the DRB are secondary forests recovering from agricultural land use, with stand ages around 80–100 years. Succession in the DRB during the recovery process may affect forest biomass C change (Xu et al., 2012). These forests are sensitive to the controlling factors defining forest dynamics; thus, quantifying the biomass C stock in DRB forests acts as the basis for regional C cycle assessment and is essential for effective forest C management.

During 2001 to 2003 a set of forested plots were established in the DRB, and their total biomass C stock (including above- and belowground biomass, but not including fine roots; see below) was measured in a multi-agency program known as the Collaborative Environmental Monitoring and Research Initiative (CEMRI). Here we report the results of re-measuring these plots using the same measurement protocols in 2012–2013. By comparing forest biomass C in the two measurements, and carefully documenting demographic changes, the major goals of this study are: (1) to quantify biomass C stock change in the DRB forest during the recent decade, (2) to investigate the controlling factors of forest biomass C stock change at the regional scale, and (3) to examine the impact of tree demographic change on biomass C change by comparing biomass C change in different size groups and tree species.

2. Methods

2.1. Research area

The Delaware River is one of the major rivers in the mid-Atlantic region of the United States, draining an area of about 33,000 km^2 in Pennsylvania, New Jersey, New York, Delaware, and Maryland. The Delaware River Basin is characterized by a humid continental climate, with mean annual temperature of 9–12 °C and mean annual precipitation of 1143 mm (Kauffman et al., 2008). The DRB is located in the eco-zone of deciduous forests and is ecologically diverse, comprised of five physiographic provinces and multiple species assemblages that represent most of the major eastern U.S. forest types (Murdoch et al., 2008).

Three areas in the DRB were selected as intensive monitoring and research sites for process-level studies in forested landscapes: the Neversink River Basin (NS) in the northern, mostly forested region of the Appalachian Plateau province; the Delaware Water Gap Area (DEWA) with three small watersheds (Adams Creek, Dingman's Falls and Little Bushkill) lying in the central Appalachian Plateau Province; and the French Creek Watershed (FC) in the midbasin Piedmont province (Fig. 1).

During 2001–2003, 68 inventory plots were randomly located in the three sites. Within each plot, all trees with diameter at breast height (DBH) greater than 5 inches (12.7 cm) were measured and marked, and the specific locations of the plots were mapped. In 2012–2013, 61 forested plots of the 68 original plots were revisited and biomass parameters were re-measured using the same protocols. Seven plots were not revisited due to accessibility issues such as permission from the landowner. Between the two measurements some plots had been disturbed by human activities, such as clear-cut or land use change. Anthropogenic disturbance was recorded in the field and while disturbed plots were included in the determination of biomass estimates, they were not included in the demographic analyses. The number of usable plots for demographic analyses was therefore reduced from the original 68 to 55 plots.

2.2. Field measurements and biomass C calculations

The plot design and sampling method follow the forest inventory protocols in the two measurements, including additional variables that were specified for the intensive study sites (Fig. 2; U.S. Department of Agriculture, 2014). Each plot has four round subplots, in total covering an area of 672.44 m^2. Live and dead trees, stumps and residue materials were measured in each subplot. DBH, total and bole height, tree species, and status change (e.g., live versus dead) of each tree were recorded. A laser rangefinder was used to measure the tree and bole heights. Each subplot has one microplot (area: 13.49 m^2) and three transects (length: 7.92 m). Live and dead sapling (1 in. < DBH < 5 in.), seedling (DBH < 1 in.), shrub and herb coverage were measured in the microplots. Coarse woody debris and fine woody debris were measured along the transects.

Within each plot, two trees close to the subplots that represent the dominant species and growing condition of the forest stand were selected as site trees. The age of the site trees was measured by counting rings in a tree core. The stand ages of plots were determined as the mean age of the two site trees.

Field measurement data from the original 2001 to 2003 inventory were acquired from a U.S. Forest Service (USFS) database generated by the CEMRI project (http://www.fs.fed.us/ne/global/research/drb/summary.html). Data from the two inventories were compiled into a single database for biomass C calculations. Cole et al. (2013) provides a detailed description of the database, which contains CEMRI project data on tree biomass.

Biomass of live trees, dead trees, saplings, seedlings, shrubs, coarse woody debris, fine woody debris, and stumps were each calculated and summed for each of the two survey periods. Fine root biomass was the only biomass pool not estimated in either survey in this study. As a result, we assumed that fine root biomass did not change between the two sampling periods. The species-specific allometric equations from Jenkins et al. (2004) were used to calculate above-ground tree biomass (Suppl. Table 1) as described in Cole et al. (2013). The proportion of coarse roots biomass to above-ground biomass was estimated based on DBH for each species as described in Jenkins et al. (2004) and Cole et al. (2013). The total biomass of each tree was the sum of above-ground biomass and coarse roots. Dead tree biomass was multiplied by a reduction factor according to their decade classes and species groups (Waddell, 2002) to subtract the biomass loss from decomposition. Biomass of coarse woody debris and fine woody debris were calculated using standard equations (Woodall and Williams, 2005). Stump biomass was calculated as coarse root biomass multiplied by the reduction factor according to the decade classes. A conversion factor of 0.5 was used to convert biomass to C stock. The biomass C change of