

QUANTIFYING CARBON SEQUESTRATION IN FOREST PLANTATIONS BY MODELING THE DYNAMICS OF ABOVE AND BELOW GROUND CARBON POOLS

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Abstract—Intensive pine plantation management may provide opportunities to increase carbon sequestration in the Southeastern United States. Developing management options that increase fiber production and soil carbon sequestration require an understanding of the biological and edaphic processes that control soil carbon turnover. Belowground carbon resides primarily in three pools: roots, necromass (litter, roots), and soil. There is little evidence that intensive management affects mineral soil carbon. Conversely, perennial root systems contribute to carbon sequestration through formation of long-lived belowground biomass and carbon in root necromass and woody debris that may persist for years following harvest. Due to their large mass and physicochemical composition, these dead coarse roots require decades to decompose. If the length of the decay process extends beyond the length of the next harvest rotation, it will result in an accumulation of soil carbon. Increasing productivity and shortening rotation length may accelerate carbon sequestration over successive rotations. Further, management activities that retain forest floor and slash material or incorporate organic materials into the soil during site preparation may also increase soil carbon.

INTRODUCTION

Forests are being considered as one option for stabilizing or reducing atmospheric carbon dioxide (CO₂). Forests can reduce atmospheric CO₂ by storing carbon in biomass, soil, and products and can be used as biofuel offsetting fossil fuel (Birdsey and Heath 2001). However, forests grown into perpetuity will provide no long-term CO₂ reduction because eventually carbon losses will equal or exceed carbon gain. Management of forest carbon sequestration should be viewed as a temporary mitigation effort spanning 50 to 100 years as new technologies to store carbon or reduce carbon emissions are developed. Carbon capture in forest growth provides a low cost approach for meeting State and national carbon sequestration goals and can be accomplished with available technology.

Forests will likely never be managed solely for carbon sequestration (Johnsen and others 2004). However, the potential economic value of emission credits from carbon sequestration might provide a co-benefit that, depending on financial value, could affect management practices (Birdsey 2006). Intensive pine plantation management may provide opportunities to increase carbon sequestration in the Southeastern United States. An understanding of the biological and edaphic processes that increase and retain soil carbon is required so that management can be modified to increase fiber production and soil carbon sequestration.

MULTIPLE ROTATION CARBON DYNAMICS

Managed forests can provide in-situ (biomass and soils) and ex-situ (products) pools for carbon sequestration (Johnsen and others 2001). Intensive management utilizing improved silviculture, fertilization, and genetically superior planting stock has increased aboveground loblolly pine productivity threefold (Borders and Bailey 2001) and decreased rotation lengths. Less is known about how plantation forestry affects the stand carbon balance (Johnsen and others 2001, 2004). Belowground biomass carbon and fluxes is the weakest link in our understanding of forest carbon cycling. There is little

evidence that silviculture and intensive management affects, either positively or negatively, long-term mineral soil carbon (Schlesinger 1990, Richter and others 1999, Laiho and others 2003). This is presumably because of the relatively high decomposition rates of newly input carbon and the low rate of carbon incorporated into organo-mineral complexes (controlled by soil physical properties).

Additionally, most studies have been conducted during the first rotation following the abandonment of agriculture (Richter and others 1999) or soil sampling has randomly or even systematically (Laiho and others 2003 Schlesinger 1990,) avoided regions intimately associated with stumps where decomposition rates of large coarse roots are slower. Thus, given little evidence of the potential of forest management to increase mineral soil carbon, we concentrate here on examining the dynamics of root biomass and necromass and their contribution to belowground carbon storage. Along with aboveground pools, we consider the potential of forest management to provide short- or medium-term carbon sequestration.

In-situ plantation carbon dynamics can be conceived as follows: trees are planted, above and belowground biomass grows over time, trees are harvested, root biomass becomes root necromass, trees are replanted and new biomass is accreted as root necromass decomposes (fig. 1). The varying rates of these processes, the rotation age, silviculture, management, and the period for which these carbon dynamics are assessed all greatly influence the estimate of carbon sequestration. For example, intensive management practices that increase aboveground productivity results in increased belowground carbon in tap and coarse root systems (Albaugh and others 2004, Samuelson and others 2004a). Because of their relatively large mass and physicochemical configuration, these root systems require decades (20 to 60 years) to decompose (Ludovici and others 2002). If the length of the decay process extends beyond the length of the next rotation, it will result in an accumulation

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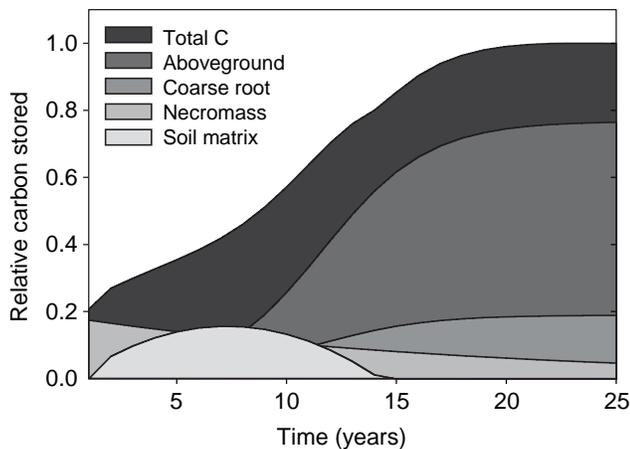


Figure 1—Conceptual changes in carbon storage in a pine plantation in aboveground and belowground pools over a 25-year rotation. Changes in soil matrix carbon reflect changes in the organic matter carbon pool above a baseline.

of soil carbon. Additionally, large increases in soil carbon occur after harvesting, presumably from recently severed root system and decomposing litter (Johnsen and others 2004, Van Lear and others 1995). This pool consists of light fraction carbon or free organic matter that is not physically or chemically bound in organo-mineral aggregates and will not persist through the next rotation. There is evidence that management practices such as fertilization may decrease the rate of carbon loss from this pool (Butnor and others 2003, Pangle and others 2002, Samuelson and others 2004b). While carbon in decomposing root systems and litter is relatively labile compared to recalcitrant mineral soil C, these pools are easily manipulated and may offer an opportunity to increase carbon sequestration in short rotation plantations. Johnsen and others (2004) hypothesized that combining increased aboveground productivity with shorter rotation lengths will increase belowground carbon sequestration over multiple rotations in intensively managed pine plantations.

Here we demonstrate simple examples of stand carbon dynamics to illustrate how intensive forestry and rotation length can potentially alter site carbon storage over successive rotations. We also explore management impacts on carbon sequestration and identify its key drivers as well as the most critical information needed to improve the reliability of estimates across different site types. There are numerous carbon action programs at the global, national, and State levels, and U.S. forests are being registered for potential future carbon credits; however, there is no certified method to estimate forest carbon sequestration. We illustrate what we consider the correct approach to calculate short- to medium-term carbon sequestration in intensively managed forest plantations.

MATERIAL AND METHODS

We empirically modeled loblolly plantation carbon dynamics of four carbon pools: aboveground biomass, coarse roots, root necromass, and soil matrix organic matter (fig. 1). We then compare simulated multiple rotation carbon sequestration for stands receiving different levels of management.

We used stem biomass growth curves developed for a high productivity, short rotation research plantation (Martin and Jokela 2004). In these stands, reducing nutrient limitations through weed control and/or fertilization resulted in dramatic increases in stem production (fig. 2). In addition, alleviating soil nutrient limitations accelerated stand development such that treated stands reached 95 percent of maximum stem biomass about five years earlier (arrows, fig. 2) than non-treated controls.

Aboveground biomass was calculated as a fixed proportion of stem biomass [i.e., $AG_{biomass} = 1.52 * \text{stem biomass}$ (Albaugh and others 1998)]. Root system biomass was accreted from coarse root allometry shown in Johnsen and others (2004) using data derived from a wide range of sites, stand age, and productivity. Root necromass attenuation was estimated using an empirical model from Ludovici and others (2002). Fine fraction soil organic matter dynamics from 0 to 30 cm were estimated by equations fitted to soil carbon from Johnsen and others (2004) adjusted for initial root necromass estimated at the beginning of each rotation. This pool represents the ephemeral increase in soil matrix carbon above an unchanging baseline. Carbon was estimated by multiplying biomass by 0.5.

Simulations examined carbon dynamics in the various pools over a 60-year project period for three treatment scenarios: no treatment (NT), weed control (WC), and fertilizer plus weed control (FWC) (Martin and Jokela 2004). Treatment effects on carbon sequestration were compared for three 20-year rotations and four 15-year rotations in the case of WC and FWC treatments. We assumed that the site was managed as a loblolly pine plantation prior to the project. Curves for biomass, necromass and organic matter C carbon were calculated as above, the area was integrated under each curve (fig. 1), and the sum of the integrated values was divided by 60 (years) to provide an estimate of mean-integrated carbon stored per year (i.e., $Mg\ C\ ha^{-1}yr^{-1}$).

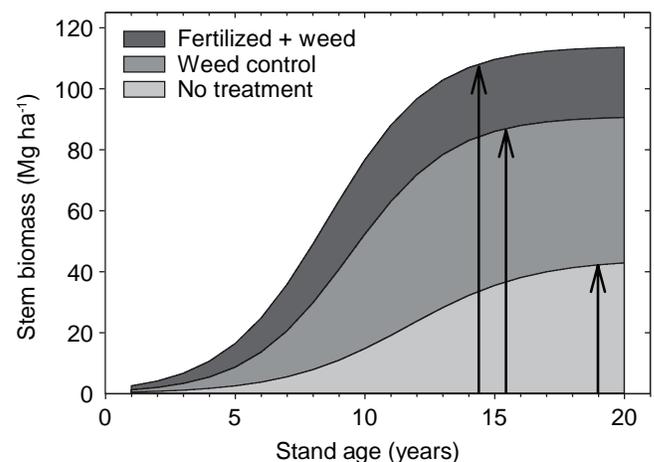


Figure 2—Stem biomass accumulation for three silviculture treatments: no treatment (NT), weed control (WC), and fertilization and weed control (FWC) derived from growth equations (Martin and Jokela 2004). Arrows indicate time when stand reaches 95 percent of maximum stem biomass.

RESULTS

Total carbon accumulation in the NT scenario approached 45 Mg C ha⁻¹ in each of the three successive 20-year rotations (fig. 3a). In contrast, maximum total carbon accumulation was substantially higher in the WC (data not shown) and FWC (fig. 3b) scenarios and increased over successive rotations. This corresponded to a mean integrated total carbon (above + belowground) of 28.0, 61.9, and 80.7 Mg C ha⁻¹ y⁻¹ in the NT, WC, and FWC scenarios, respectively, over the 60-year period (table 1). Root necromass increased over time in the WC and FWC scenarios because root decomposition exceeded the rotation length (fig. 4a). The WC and FWC stands maintained 10.7 and 16.3 Mg C ha⁻¹ y⁻¹ more belowground carbon, respectively, than did the NT over the project period (table 1). Decreasing rotation length resulted in less accumulated total carbon in the WC and FWC (fig. 3c) stands and 10 to 12 percent less total mean-integrated carbon maintained on site (table 1). However, shorter rotations resulted in an increase in belowground carbon accumulation (fig. 4b), in mean integrated belowground carbon storage, and in carbon of harvested biomass (table 1). Thus, while the longer rotation length increased the total mean integrated carbon storage; shorter rotations resulted in increased belowground carbon storage and carbon stored in harvested biomass.

DISCUSSION

These scenarios demonstrate that stand productivity and rotation length potentially can influence in-situ carbon storage over successive rotations in short-rotation pine plantations (e.g., pulpwood, biomass for energy). Weed control and/or fertilization, greatly increased aboveground production and resulted in increased belowground carbon sequestration in living coarse root systems, necromass, and soil organic matter. Furthermore, while longer rotation lengths had higher mean-integrated total in-situ carbon storage, increased productivity combined with shorter rotations resulted in more belowground carbon storage and carbon in harvested biomass. This is due to increasing the overlap in accumulation of new biomass and the loss of necromass and soil organic matter through decomposition. These scenarios illustrate the importance of these ephemeral carbon pools (root necromass and organic matter) in the carbon budget of intensively managed plantations.

The most limiting aspect of these calculations all involve estimates of belowground carbon allocation and residence times. Ludovici and others (2002) estimated loblolly pine taproot decomposition from a chronosequence beginning with a 60-year-old plantation. Short rotation, high-productivity plantations have taproots that are chemically dissimilar to older trees and likely decompose at a faster rate under similar soil conditions. We know very little about taproot growth and decomposition processes in plantation forests or the variation in these processes across genotype (species), site conditions, disturbance regimes, and climate. For example, Ludovici and others (2002) examined trees on a well drained Piedmont soil. Loblolly pine plantations along the coastal plain are often planted on moderately to poorly drained sites with high water tables. Even in very high productivity plantations, these sites are often inundated for large portions of the year. Anaerobic conditions reduce initial necromass decomposition rates and probably increase the residence time of root necromass. On the other hand, site preparation activities such as disking, bedding, chopping or burning may accelerate root necromass decomposition during stand reestablishment (Gough and others 2005). Given the importance of the overlap of root biomass growth and root necromass decomposition, realistic estimation of coarse root decomposition is critical for quantifying in-situ carbon sequestration, particularly when rotation length is short.

The simulations ignored carbon stored in perennial hardwood root systems. Hardwoods would be an important carbon component in the NT scenarios. Miller and others (2006) found after 25 years of plantation growth, silviculture practices (chop and burn or shear-pile disk) that increased aboveground pine production had no effect on total coarse root biomass when hardwoods were considered. Thus, we could assume that hardwood biomass would make up most of the difference in mean integrated carbon storage between the NT and WC scenarios. However, Martin and Jokela (2004) found that the WC and FWC increased site carrying capacity, which probably results in increased mean integrated carbon storage. For example, comparing FWC and WC scenarios, fertilization increased mean integrated belowground carbon storage by 25 to 38 percent depending on rotation length.

Table 1—Simulated mean integrated carbon storage over a 60-year project period

Treatment	Rotation years	Total C storage	Aboveground C storage	Belowground C storage	Δ BG	Harvested biomass
		-----Mg C ha ⁻¹ yr ⁻¹ -----				Mg C ha ⁻¹
NT	20	28.0	14.8	13.2		197.1
WC	20	61.9	38.0	23.9	10.7	271.8
FWC	20	80.7	51.2	29.5	16.3	340.8
WC	15	54.4	28.0	26.4	13.2	344.0
FWC	15	72.9	39.8	33.1	20.0	438.4

Note: Carbon (C) storage in aboveground, belowground, and harvested biomass are compared for 20-year and 15-year rotations for stands under a range of treatments: no treatment (NT), weed control (WC), and fertilization plus weed control (FWC). Δ BG is the increase in belowground C storage compared to No Treatment.

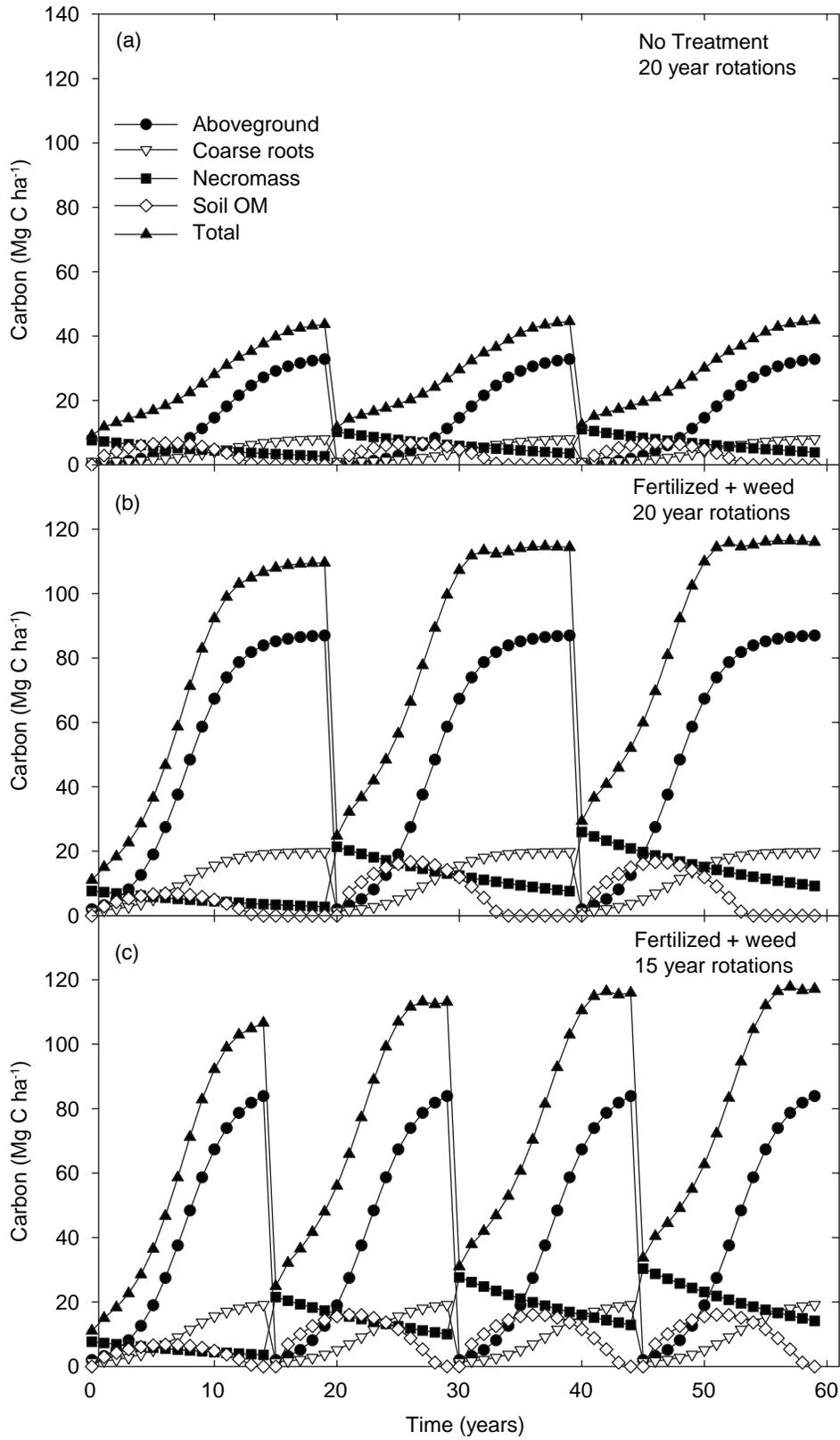


Figure 3—Simulated stand carbon (C) accumulation over three 20-year rotations for stands receiving (a) no treatment (NT) or (b) fertilizer plus weed control (FWC) and (c) over four 15-year rotations for FWC.

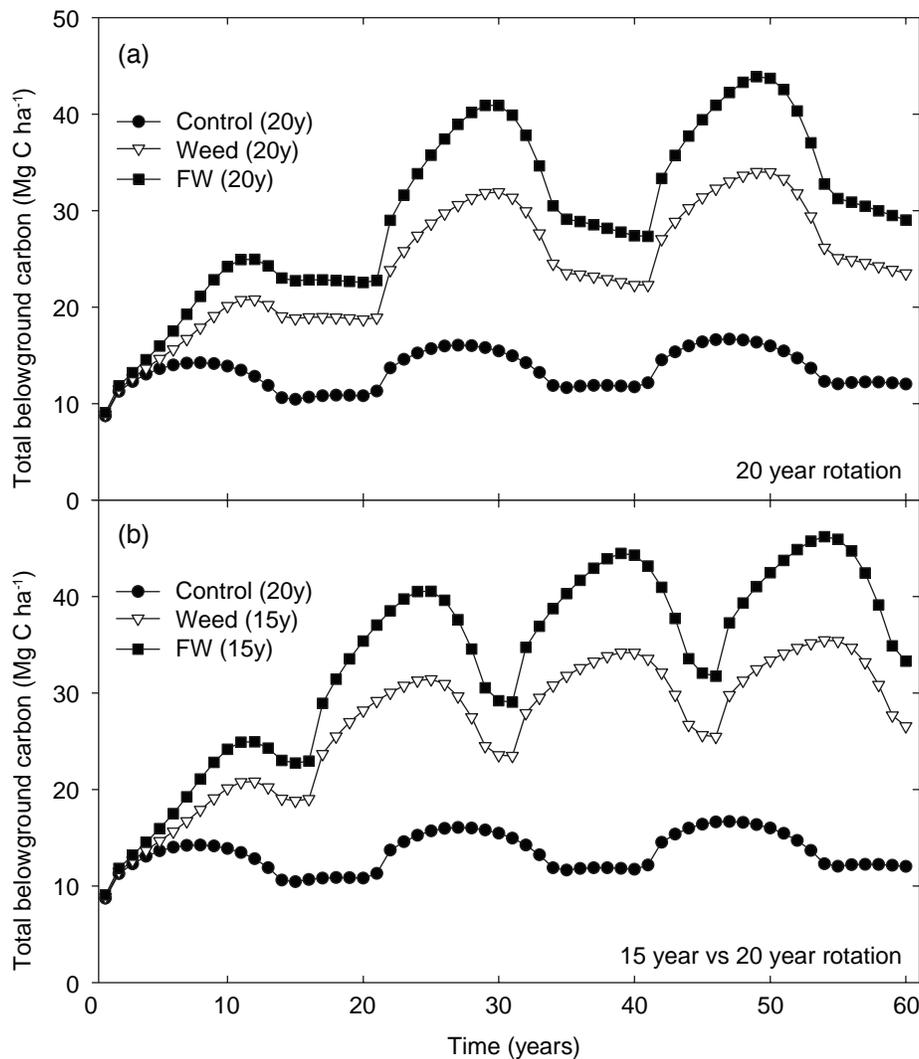


Figure 4—Simulated belowground carbon (C) accumulation for stands receiving either no treatment (NT), weed control (WC), or fertilization plus weed control (FWC). Comparisons show treatment responses for (a) 20-year rotations and for (b) 15-year (WC, FWC) versus 20-year (NT) rotations.

Aboveground carbon allocation was fixed with time and treatment. While aboveground metrics such as total biomass, stem biomass or basal area is a good predictor of coarse root mass (Johnsen and others 2004), root to shoot ratios vary with stand development and site productivity (Albaugh and others 2006) and species. A better understanding of the physiological controls of carbon allocation is needed for modeling short rotation forest carbon budgets.

Although forests in the U.S. are being registered for potential carbon credits, there is no certified method to estimate forest C sequestration. Simple estimates of carbon accumulation based on net carbon stock (e.g., live biomass, mineral soil C) (Birdsey 2006) changes over an interval will not be sufficient for estimating the carbon budgets of short rotation plantations. We suggest that the mean integrated approach that incorporates dynamic changes in soil organic matter and root decomposition following harvesting is the more appropriate method for quantifying site carbon for short

rotation plantations. Accounting for site-specific effects on these ephemeral pools will improve the precision of carbon estimates.

CONCLUSIONS

The analyses shown in this study, while informative, are simple and not sufficient to quantify marketable carbon credits. However, we contend our approach is the most valid way to address the problem. Our results suggest that short-rotation; high-productivity forests potentially can be managed for carbon sequestration, and management practices that optimally increase productivity and retard necromass decomposition will provide the greatest carbon sequestration.

Clearly, our ability to quantify coarse root decomposition in young plantations under varied environmental conditions represents our weakest area of understanding and is critical for conducting realistic analyses using our approach.

In addition, mechanistic studies are needed to better understand the variation associated with genotype (within and among species) and G x E interaction in carbon accretion, retention, and loss patterns. Regardless, carbon sequestration will need to be estimated for forests sooner rather than later. The value of C credits should be tied to the precision and accuracy of carbon sequestration estimates (Birdsey 2006, Johnsen and others 2004). Further research should endeavor to improve accuracy of estimates across a broad array of forest conditions.

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