ASSESSMENT OF FOREST MANAGEMENT INFLUENCES ON TOTAL LIVE ABOVEGROUND TREE BIOMASS IN WILLIAM B. BANKHEAD NATIONAL FOREST, ALABAMA

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Abstract-- Forests contain a large amount of carbon (C) stored as tree biomass (above and below ground), detritus, and soil organic material. The aboveground tree biomass is the most rapid change component in this forest C pool. Thus, management of forest resources can influence the net C exchange with the atmosphere by changing the amount of C stored, particularly in landscapes dominated by forests, such as in the southeastern United States. Our work focuses on the influence of prescribed burning and thinning on total live aboveground tree (TLAT) biomass in the William B. Bankhead National Forest, Alabama. We implemented a large-scale study that involved a factorial arrangement of three levels of thinning (heavy thin to 11 m^2 ha^{-1} basal area; light thin to 15 m^2 ha^{-1} basal area; and no thin) and three prescribed fire intervals (no fire, 3-year return, 9-year return). Biomass was assessed among treatments using allometric equations related to tree species and diameter. Pre-treatment stands ranged from 117 to 137 Mg ha^{-1} TLAT biomass. Overall burning showed no significant influence on TLAT biomass. All but one treatment (light thin, no burn) had a higher rate of TLAT biomass gain post-treatment than the control. Control had an average yearly TLAT biomass gain of 4 percent per year, with the thinned treatments having averages ranging from 5 percent to 7 percent per year. Our results provided a first step for reliable and accurate measurement of biomass potential, which is increasingly important, particularly for sustainable forest management, monitoring global climate change, and forest productivity.

INTRODUCTION

Over the last 30 years, carbon dioxide (CO_2) emissions from the use of fossil fuels has grown at an average rate of 1.9 percent per year (Nabuurs and others 2007). Mitigation of atmospheric CO_2 requires an approach that combines CO_2 emission reductions with increased CO_2 storage (Birdsey and others 2006, D'Amato and others 2011, Malmsheimer and others 2008). Forests contain a large amount of carbon (C) stored as tree biomass (above and below ground), detritus, and soil organic material (Fahey and others 2010) and as such have the potential to play a crucial role in the mitigation of atmospheric CO_2 through increased C storage (D'Amato and others 2011, Nabuurs and others 2007). Areas of deforestation, such as tropical rainforests, can be large sources of C (Canadell and Raupach 2008), and areas of growing forest can be large C sinks. It has been estimated that forest ecosystems contain approximately half of the total terrestrial C pool (Dixon and others 1994) and, at a global scale, forests sequester 1.3 to 4.2 $GtCO_2$-equivalents (1.3 to 4.3 billion tonnes) per year (Nabuurs and others 2007). Currently in the United States, forests sequester enough C each year to offset 10 percent of annual emissions from fossil fuels (Birdsey and others 2006).

In the southeastern United States, forests make up over 60 percent of the land area (Wear and Greis 2012). The most rapid component of forest change in this C pool is the aboveground tree biomass (Fahey and others 2010). Thus, management of forest resources can influence net C exchange with the atmosphere by changing the amount of C stored (Canadell and Raupach 2008, Malmsheimer and others 2008). It has been suggested that net C sequestration can theoretically be maximized by maintaining the landscape at a maximal stage of net ecosystem productivity (Fahey and others 2010), and that forest management targets both mitigation (using the forest to sequester C) and adaptation (increasing forest health and resiliency) (Malmsheimer and others 2008). Changing species composition, rotation length, fire, harvest management practices, and other

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biotic and abiotic disturbances can have important impacts on biomass, C stocks, and fluxes (Malmsheimer and others 2008).

This study assessed the influence of prescribed burning and thinning practices on biomass change over a 3-year period within the William B. Bankhead National Forest, in the southeastern United States. We used biomass as a surrogate for C storage; biomass estimates can be converted to C estimates using a factor of 50 percent C (Brown and others 1986, Hall and Uhlig 1991, Marland and Schlamadinger 1997).

METHODS

Study Area

The study was implemented in the William B. Bankhead National Forest (BNF; fig. 1) as part of a broader collaborative effort to experimentally test the ecosystem responses of the conversion of predominantly pine stands to upland hardwood forest cover type. The BNF was established by proclamation in 1914 and has a long history of repeated logging and of soil erosion caused by poor farming practices during the Depression era. The 73 000-ha BNF is in the Strongly Dissected Plateau sub-region of the Southern Cumberland Plateau, within the southern Appalachian Highlands (Smalley 1979). Study stands are located on slightly undulating tabletop sites, and stands are non-managed loblolly pine (*Pinus taeda* L.) plantings established 25 to 45 years ago and with substantial hardwood encroachment. Under the current management plan, much of the area is under restoration to a hardwood-dominated system (USDA Forest Service 2003). Base age 50 site indices for loblolly pine, red oaks [northern red oak (*Quercus rubra* L.), black oak (*Q. velutina* Lam.), scarlet oak (*Q. coccinea* Münchh.), and southern red oak (*Q. falcata* Michx.)], and white oaks [white oak (*Q. alba* L.) and chestnut oak (*Q. prinus* L.)] are 23-, 20-, and 20-m, respectively (Smalley 1979).

Within the BNF, a randomized complete block design with a 3 x 3 factorial treatment arrangement and four replications of each treatment was used to assess the impact of burning and thinning. The treatments were three thinning types (heavy thin 11.5 m^2 ha^{-1} residual basal area, light thin 17.2 m^2 ha^{-1} residual basal area, and an unthinned control) with three fire frequencies (burns every 3 years, burns every 9 years and an unburned control) (table 1). Each treatment is replicated four times for a total of 36 stands. Treatments were representative of management practices described in the BNF's Forest Health Restoration Plan for restoring upland oak-dominated forests and woodlands (USDA Forest Service 2003).

Field Methods

We established five, 0.08-ha vegetation measurement plots in each stand. All plot centers were permanently marked with rebar and flagging, and GPS coordinates were recorded. All trees ≥14.2 cm in diameter at breast height (d.b.h.) were permanently marked with aluminium tags, identified to species, and d.b.h. was measured. Stand selection and data collection began in the summer of 2004 and, to date, three vegetation measurements at each treatment stand were taken: pre-treatment, immediately post-treatment, and 3 years post-treatment. Frequently burned stands had received two burns, and infrequently burned stands received one burn; all burns are dormant-season burns, occurring between January and March.

Data Analysis

We used total live aboveground tree biomass (TLAT biomass) as the total aboveground biomass, calculated using allometric equations (Jenkins and others 2004). The TLAT is defined as the aboveground mass of wood and bark in live trees ≥ 14.2 cm d.b.h. from the ground to the tip of the tree, excluding all foliage (leaves, needles, buds, fruit, and limbs < 13 mm in diameter). TLAT biomass is expressed as oven-dry mass, and the unit is kg $tree^{-1}$. Equations of individual tree TLAT biomass have been developed for most tree species or species groups in the United States (see for example Jenkins and others 2004). The TLAT biomass was calculated for each tree using Jenkins and

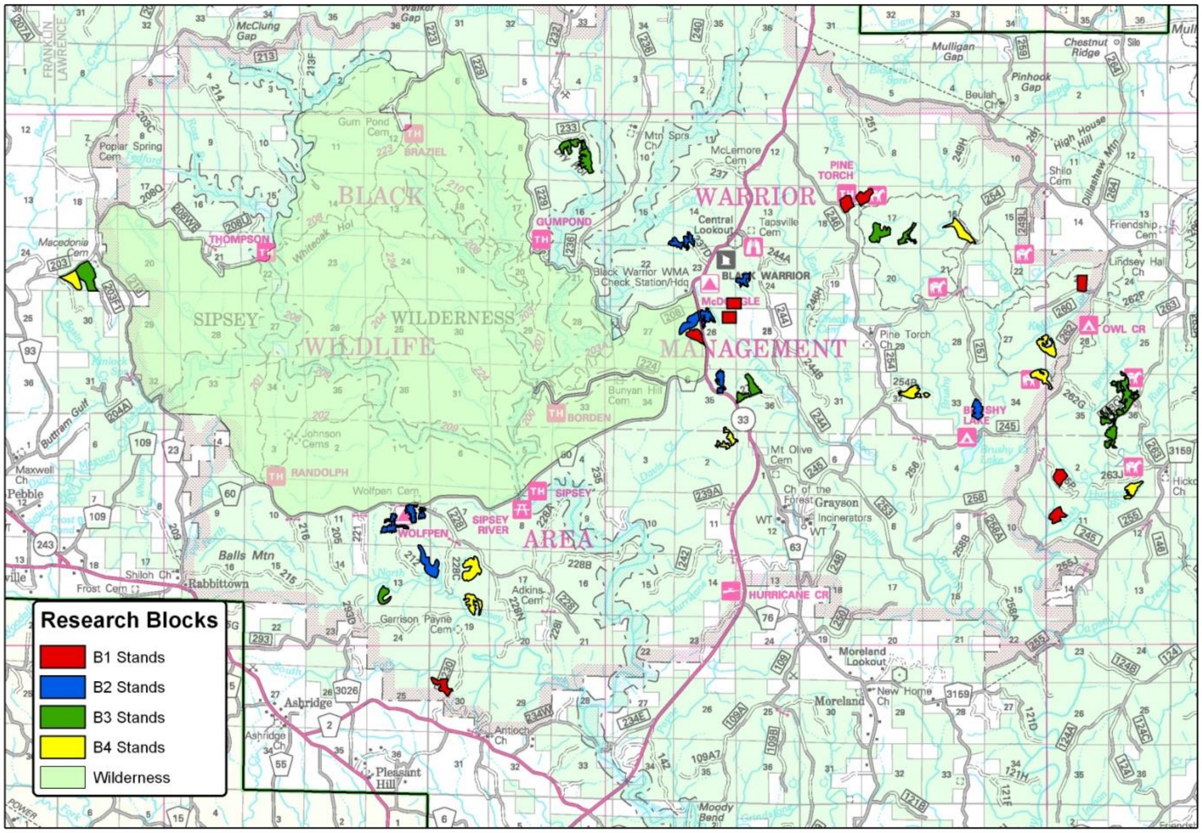

Figure 1--Map of the William B. Bankhead National Forest in north-central Alabama with depiction of study stand locations.

Table 1--Management treatments for silvicultural research on the William B. Bankhead National Forest, Alabama

Treatment number	Treatment
1	Control (no thin, no burn)
2	No thin, infrequent burn (9 years)
3	No thin, frequent burn (3 years)
4	Heavy thin (11.5 m^2/ha residual stand density), no burn
5	Light thin (17.2 m^2/ha residual stand density), no burn
6	Heavy thin, frequent burn
7	Light thin, frequent burn
8	Heavy thin, infrequent burn
9	Light thin, infrequent burn

others (2004) equations with Mg ha^{-1} calculated for each plot and stand for all species combined, all pine, and all hardwoods. We assessed productivity by evaluating the proportion gain in TLAT biomass across treatments.

Analyses of variance was used to assess the nine treatments pre-treatment, treatment against post-treatment, gain between immediate post-treatment and 3 years after post- treatment, and proportional gain between immediate post-treatment and 3 years after post-treatment. Pairwise comparisons using Tukey's contrasts were applied when appropriate. These analyses were performed using data sets containing: all trees, pines only, and hardwoods only. This included assessment of pre-treatment differences and productivity differences post-treatment.

RESULTS AND DISCUSSION

We permanently marked and measured 10,172 trees for this study. Pre-treatment basal area (BA in m^2 ha^{-1}) in the study stands ranged from 27.9 to 31.8 [standard deviation (std) 4.8 to 6.2], and stems ha^{-1} (SPH) ranged from 1,155 to 1,386 (std 227 to 349) (Schweitzer and Wang 2013). We found no differences for BA [$F = 1.25$ (8, 24), $p = 0.88$] and SPH [$F = 0.82$ (8, 24), $p = 0.86$] among the 9 treatments prior to treatment implementation (table 2). Average tree TLAT biomass pre-treatment ranged from 150 to 206 kg with std between 110 and 180. We tallied 23 dominant or co-dominant tree species. Loblolly pine (838 SPH) and Virginia pine (*P. virginiana* Mill.) (240 SPH) were the most prevalent species pre-treatment, and yellow poplar (*Liriodendron tulipifera* L.) (46 SPH) and chestnut oak (37 SPH) were the most common hardwoods. The thinning treatments resulted in three different levels of residual BA and SPH. Unthinned stands had a BA of 30.2 m^2 ha^{-1} and 1,243 SPH; the light thinned had 15.6 m^2 ha^{-1} BA and 490 SPH; and the heavy thinned stands had a BA of 11.5 m^2 ha^{-1} and 372 SPH.

TLAT Biomass by Treatments

There was no difference in TLAT biomass among stands assigned to different treatments [$F = 0.64$ (8, 24), $p = 0.76$] or blocks [$F = 1.19$ (3, 24), $p = 0.34$] before the treatments were applied. As expected, the overall TLAT biomass decreased immediately post-treatment for all the thinned treatments, with an increase in biomass 3 years post-treatment (table 2). Three years after treatment, the total increase in TLAT biomass was different among treatments [$F = 32.43$ (8, 24), $p < 0.01$]. Pairwise comparison showed control and burn only treatments different from all thinning and thinning/burn treatments (table 2).

We found an effect of treatment on productivity [$F = 5.96$ (8, 24), $p < 0.001$]. Control productivity was different from all thinning treatments apart from the light thin with no burn. No thin, infrequent burn was only different from one treatment, the heavy thin, no burn (table 2). The thinning treatment resulted in the higher biomass productivity (table 2), but there was no difference between heavy thin and light thin. Treatments 1 and 2 had the lowest productivity among all treatment types.

Pine TLAT Biomass

The pine TLAT biomass pre-treatment ranged from 98 to 116 Mg ha^{-1}, with between 258 SPH and 933 SPH in each treatment stand. There was no difference in treatments [$F = 0.48$ (8, 24), $p = 0.86$] pre-treatment (table 3). There was an increase in TLAT biomass for the control (treatment 1) and the burn only (treatments 2 and 3) treatments for both post-treatment measurements. As expected, the overall TLAT biomass declined post-treatment for all the thinned treatments, with substantial increase 3

Table 2--Mean of basal area, stem density, and total live aboveground tree biomass by treatment for three measurement cycles, change in biomass and percent productivity. Column values with the same letters are not significantly different at 0.05

	Pre-treatment			Immediate post-treatment			3-years post-treatment			Change in biomass	Percent productivity
Treatment	BA	Density	Biomass	BA	Density	Biomass	BA	Density	Biomass		
	m^2/ ha	*stems/ha*	*Mg/ha*	*m^2/ha*	*stems/ha*	*Mg/ha*	*m^2/ha*	*stems/ha*	*Mg/ha*	*Mg/ha*	*%*
Control (1)	30.2 (4.8)	1,155 (235)	136 (17.3)	31.6a (4.8)	1,150b (235)	144a (15.6)	33.8a (4.7)	1,172b (227)	157a (17.0)	13.1ab	9.2a
No thin, Infrequent bum (2)	28.2 (6.1)	1,225 (283)	124 (11.3)	29.2a (6.7)	1198b (301)	134a (7.8)	31.4a (7.5)	1,207b (340)	148a (10.9)	16.4ac	12.5ab
No thin, frequent bum (3)	27.9 (6.2)	1,386 (331)	119 (23.7)	29.9a (6.2)	1381a (331)	128a (22.1)	33.5a (5.8)	1,447a (305)	147a (19.3)	18.3a	15.1ac
Heavy thin, no bum (4)	30.2 (5.2)	1,290 (331)	133 (10.2)	11.6cd (2.3)	375c (105)	57b (8.5)	13.6cd (2.5)	392c (96)	69b (10.6)	12.0ab	21.5c
Light thin, no bum (5)	30.5 (5.4)	1,190 (349)	139 (15.4)	15.5bc (4.3)	462c (161)	77b (13.7)	17.3bc (4.5)	471c (157)	88b (14.3)	10.8bc	15.3ac
Heavy thin, frequent bum (6)	29.3 (6.0)	1,211 (266)	128 (8.7)	11.5cd (2.1)	366c (83)	54b (7.0)	13.0d (2.2)	375c (83)	63b (8.0)	9.4b	17.8bc
Light thin, frequent bum (7)	30.3 (5.9)	1,277 (270)	130 (18.4)	14.8bcd (2.7)	471c (78)	68b (8.5)	17.2bcd (3.0)	484c (83)	81b (10.5)	13.7ab	20.5bc
Heavy thin, infrequent bum (8)	30.3 (5.1)	1,307 (227)	131 (20.7)	11.4d (2.2)	375c (65)	54b (11.1)	13.1cd (2.2)	379c (83)	64b (10.9)	10.3bc	20.1bc
Light thin, infrequent bum (9)	31.8 (5.7)	1,329 (248)	139 (20.6)	16.4b (3.8)	536c (65)	78b (16.1)	19.0b (4.2)	558c (74)	92b (19.9)	13.9ab	18.0bc
Treatments (p value)	0.41	0.17	0.76	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Treatments (F value)	1.03	1.47	0.61	85.77	101.09	32.15	89.67	103.43	32.43	6.69	5.96

Table 3--Biomass for all pines and all hardwoods separate, for pre-treatment and 3-years post-treatment

	Average pre-treatment biomass	Average 3 year post-treatment biomass	Treatments, pre-treatment	Block, pre-treatment	Treatment effect on productivity	Average productivity
	---------------*Mg/ha*	------------------	-----------------------	*p value*	------------------------	*%*
Pines	108	79	0.86	<0.01*	<0.01*	14
Hardwoods	23	22	0.96	0.02*	0.18	19

[a]Asterisk designates significant difference among treatments at 0.05

years post-treatment. There was a difference between treatments for productivity after treatment [F = 3.52 (8, 24), $p < 0.01$]. Productivity for the control (treatment 1) was lower than for heavy thin no burn (treatment 4), light thin frequent (treatment 7), and heavy thin infrequent burn (treatments 8), with the thinning having higher productivity.

Hardwood TLAT Biomass

Hardwood TLAT biomass pre-treatment ranged from 17 to 28 Mg ha^{-1}, with between 16 and 250 SPH in each stand. There was no difference in treatments [F = 0.29 (8, 24), p = 0.96] pre-treatment (table 3). There was an increase in TLAT biomass for the control (treatment 1) and the burn only (treatments 2 and 3) treatments for both post-treatment measurements. As expected, the overall TLAT biomass declined post-treatment for all thinned treatments, with substantial increase 3 years post-treatment. However, there was no difference between treatment productivity after treatment [F = 1.6 (8, 24), p = 0.18] (table 3). The percent change in biomass between post-treatment and 3 year post-treatment was higher than that for pines, ranging from 12 to 41 percent, compared with 7 to 19 percent for pines (table 3). There is more variation in productivity across the thinned stands compared to the unthinned stands.

Silviculture Studies for Biomass

This analysis was undertaken to capitalize on a large-scale study of management techniques applied to aid progression of unmanaged mixed pine-hardwood forests towards upland hardwoods. One of the values of establishing long-term, stand-level silviculture studies is the flexibility in using the data for myriad objectives. Thinnings in this study were used to target both retained species (with an emphasis on hardwoods) and removed species (with an emphasis on pines). A consequence of this is an initial removal of biomass (and sequestered C), but with the potential to increase residual tree productivity. Prescribed fire is the other treatment in this study. For TLAT, prescribed fires at low intensities (cool, dormant season burns) had no direct impact on the biomass of the overstory trees. Neither of these practices was implemented to increase biomass or C storage. However, it has been reported that C (stored in aboveground biomass) can be released back to the atmosphere via disturbances such as wildfires or prescribed burns (Birdsey and others 2006, Canadell and Raupach 2008). Chiang and others (2008) also found no effect of dormant season fires on aboveground biomass except for a reduction in oak biomass; they also found an increase in stem mortality. We have not observed any increase in mortality 3 years post-burning in our study.

Post-treatment average tree TLAT biomass all increased. For the control (treatment 1) and burn only treatments (2 and 3), this is through tree growth and ingrowth over the 3 year sampling period. In the unthinned stands, 9 SPH were counted as ingrowth for the hardwoods and 3 SPH as ingrowth for the pines. For the thinned stands, the increase in average tree biomass was more substantial (about 80 kg), suggesting the thinning had some selection towards removing smaller trees. Increased growing space also increased the recruitment of new stems but only for the hardwoods (ingrowth of 2 SPH after 3 years). These young stands contained predominately smaller diameter trees, and thinning targeted those trees in the 15 to 31 cm diameter classes. There were few tallied trees of any species with a d.b.h. > 46 cm for the 24 stands that were thinned. For both the heavy- and light-thinned treatments, pine SPH in the15-cm d.b.h. class was reduced 90 percent. There was a 78 percent reduction in 20-cm pine and a 65 percent reduction in 25-cm pines.

Three seasons post-treatments, both the light- and heavy-thin stands increased productivity at 18.8 percent, compared to a 14.9 percent for the unthinned stands. Horner and others (2010) also found that moderate thinning resulted in the highest C storage rate, and that the lowest C storage was found in untreated stands. The sustainability of this short-term gain will be impacted by the age, diameter, and species distribution of the residual trees which may or may not continue to respond over time (D'Amato and others 2011, Hoover and Stout 2007). As these stands contained 23 tree species with dominant or codominant crown status, it is possible that stand dynamics, including ingrowth and residual growth, will shift with time and other disturbances (the continuation of the prescribed burns, wind events). Maintaining and enhancing diverse systems with various species, sizes, and functional groups are keys to resiliency to future disturbances, including climate change (Malmsheimer and others 2008, Ruddell and others 2007). Although stocking levels have been shown to explain variation in biomass and C stores, stocking of desirable species, or of species that may be more apt to continue to increase in biomass, are unknowns in these mixed pine-hardwood systems.

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