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Research Article

Impact of Loblolly Pine (*Pinus taeda*) Afforestation Efforts in East Texas on Soil Carbon Allocations

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ABSTRACT

Understanding ecosystem carbon dynamics is of increasing importance with atmospheric carbon dioxide (CO_2) concentrations on the rise. Land management strategies such as land use conversion, effect ecosystem carbon cycling dynamics and can alter the quantity of carbon sequestered in vegetation and soils. In East Texas and much of the southern United States, there has been a trend of converting marginal pastureland into loblolly pine (*Pinus taeda*) plantations. This afforestation, like other land use conversions, leads to a redistribution of carbon in vegetation and soil carbon sinks. Three marginal pastures in East Texas were afforested with loblolly pine and monitored to quantify the organic carbon sequestered as a result of this land use change. Fifteen years after plant, soils were sampled to assess the change in soil organic carbon in the top 40 cm of soil, as well as the accumulated 0 horizons. Two years later tap root systems and coarse roots on each of the three sites were excavated to quantify belowground biomass. All sites experienced increases in carbon sequestered belowground in coarse roots, tap roots, and O horizons. Only one site had a statistically significant increase in soil organic carbon (SO). Afforestation of these former pasturelands appears to result in significant increases in sequestered soil carbon.

Keywords: Soil carbon; Sequestration; Afforestation

INTRODUCTION

Changes in atmospheric gas composition are one of the sources of climate change, specifically the concentration of Greenhouse Gases (GHGs), including methane (CH_4), nitrogen oxides (NOx), and carbon dioxide (CO_2). Incoming solar radiation warms the surface of the earth which, in turn, reemits this thermal energy that is absorbed by GHGs and reemitted back towards earth [1]. While the majority of GHGs are naturally occurring, anthropogenic activity has led to an increase in GHGs atmospheric concentrations, with the combustion of fossil fuels and land use conversion as major contributors. Reducing the CO_2 produced from the combustion of fossil fuels is one of the primary targets to curb GHG concentrations; emissions from fossil fuel combustion is projected to peak between 2029 and 2044, and not return to atmospheric concentration below 400 ppm CO_2 for at least two centuries [2,3].

Due to the complexity of observing soil dynamics *in situ*, there is relatively little known of carbon dynamics of soil systems beyond that it is a large component of the global carbon cycle, acting as both a major sink and source for atmospheric carbon [4]. Until the 1940s, land use change was primarily the conversion of natural ecosystems; in 2008, approximately 18% of global CO_2 emissions still originated from deforestation [5]. Using afforestation as a mitigation method offers the opportunity of sequestering carbon from forest biomass, both above and below ground. Soil carbon, including soil organic carbon, biomass (roots), detritus and humus represent the largest terrestrial carbon pool, therefore afforestation has significant potential for sequestering carbon below-ground [4,6,7].

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In the southeastern United States, a popular species for afforestation is loblolly pine (*Pinus taeda*) because of its rapid growth, economic value as a timber source, and site adaptability. Loblolly pine research focused on belowground characteristics has generally been centered on fine root dynamics and seedling root:shoot ratios. Forests have the capacity to sequester carbon *in situ* (biomass, soil, litter) and *ex situ* (timber and wood products); timber used in the construction of single-family homes built before 1980 is estimated to have a half-life (the amount of time it takes for half of the carbon in wood and fiber products in use to be transformed into more mobile forms of carbon such as CO_2 or CH_4) of 80 years [8,9].

The latency of carbon in these pools varies and depends on many factors, including bioavailability and reactivity. For example, carbon may be sequestered for centuries in humus [4]. Roots can contribute organic compounds to the soil in a number of ways. Primarily, the additions of organic substances to the soil can come from the inputs of cellular materials and exudates. Carbon can be released in exudates as organic and inorganic carbon with the form of carbon depending on many factors including plant type, climate, and physical and chemical soil parameters. Carbon mobilized from plant shoots to the root system can account for 2%-30% of total dry matter production [4]. Carbon contributed from biomass and exudates are important in carbon cycling and humus production in soil environments. Loblolly pine needles decompose at a constant rate of 44% of needle dry weight remaining after one year of decomposition; it is assumed remnants will still be existing after two years of decomposition [10].

Detritus on the forest floor is primarily oxidized or modified through faunal and microbial activity, and factors that affect the respiration rates of these organisms will affect the latency of carbon stored in plant materials [11]. It is well understood that plant materials with low C:N ratios undergo faster decomposition than those with high C:N ratios [4,11]. Detritus originating from conifers have a median half-life higher than deciduous trees [11]; detritus originating from multiple sources has higher decomposition rates than from a single species [12]. A monoculture would therefore generate detritus that has a longer latency than compared to natural stands or detritus produced by mixed forests. Humification is the process in which organics from detritus and exuded organics are converted to humus through microbial decomposition. Humic substances make up 60 to 80% of humus, while nonhumic substances make up 20% to 30% [4]. Soil Organic Carbon (SOC) is derived from Soil Organic Material (SOM); the accepted conversion is SOC is equal to half of SOM [13]. The inherent variability of soils means that the accepted 0.5 conversion factor will not hold true for all SOM, but is an acceptable value for simplified modeling on larger scales.

Excavated loblolly pine root systems had 70%-75% of lateral root biomass existed in the top 20 cm of the soil, with 50% of the total root biomass attributed to the belowground stump, while found that 91.9% of the biomass in loblolly pine root systems occurs in the upper 50 cm of a soil profile. When three different stands of loblolly pine across different stand development stages and site characteristics were examined, coarse root biomass was approximately 50% of stem biomass on a per hectare basis. Rooting density decreased with depth due to a large number of factors, such as finer soil textures and higher mechanical resistance that impair root development at greater depths [14-19]. Additionally, decreases that are associated with increase depth, such as decreases in organic matter, biologic activity, aeration, and fertility, could also discourage foraging behavior associated with fine roots [19]. Fine roots compose only 1% of the biomass in loblolly pine, but account for 13% of annual biomass production [20]. Fine roots in forested ecosystems are short lived and decompose rapidly; therefore, much of the carbon in fine roots is released back into the atmosphere as CO2. The portion of dead, recognizable mass of loblolly pine tap root systems has been observed in measurable quantities 60 years post-harvest, meaning coarse roots, including tap root systems, represent a long-term carbon sink [21].

In 2001-2004, approximately 1396 hectares across eight sites of pastureland in east Texas were planted with loblolly pine as a part of a carbon sequestration project funded by STMicroelectronics Inc. in collaboration with the Arthur Temple College of Forestry and Agriculture at Stephen F. Austin State University (SFA). These plantations offered an opportunity to evaluate changes in soil carbon storage, including the contribution of carbon from coarse roots, as a result of afforestation activity.

The goal of this study was to quantify the amount of carbon sequestered in loblolly pine (*Pinus taeda*) plantations from woody coarse roots, forest litter layers (O horizons), and soil organic carbon 17 years since afforestation in Eastern Texas. More specifically, the objectives of this study were to quantify:

- Belowground coarse woody root biomass of loblolly pine for the purpose of carbon sequestration assessment.
- Carbon accumulation in forest litter (0 horizons) for the purpose of carbon sequestration assessment.
- Accumulation of soil organic carbon in a loblolly plantation setting for the purpose of carbon sequestration assessment.

MATERIAL AND METHODS

Site description

The study was conducted on three SFA Real Estate Foundation-owned properties. Two of the three sites were located approximately 16 km east of Crocket, Texas. The third site was located approximately 11 km southeast of Rusk, Texas. Each site contained 17-year-old, thinned loblolly pine plantations. Prior to planting of loblolly in 2001, each site had previously been used as pastureland for cattle forage production for several decades. One property (31°12' 53.56"N, 95°18'7. 18"W), will be referred to as Arbor Grove; the second site located 10 km northeast of Arbor Grove is Hickory Creek (31°23'28.36"N, 95°15'52.21"W). The climate data were identical for both, with a mean temperature of 18.5°C and a mean annual precipitation of 1068 mm year-1 [22]. The third site is Atoy (31°15'38.12"N, 95° 2'32.65"W), which receives a mean annual precipitation of 1259 mm year-1 with a mean annual temperature of 18.2°C [23].

Prior to planting, the Atoy site was an improved coastal bermudagrass pasture; the other two sites were a mix of coastal bermudagrass and other unimproved pastures. Arbor Grove consisted of 148.6 ha of 17-year-old loblolly pine plantation on upland. Atoy consisted of 154.1 ha of 17-year-old loblolly pine plantation on upland. Hickory Creek consisted of 17-year-old loblolly pine plantation with 85.3 ha in alluvial floodplain and 49.1 in upland. All pine plantations previously received thinning treatments in 2015-2016.

Soils at Arbor Grove were 70% Alfisols, with the dominant soil series being Lovelady (Arenic Glossudalfs) which occupied roughly 39% of the site. The remaining soils were Fluvaquentic Endoaquepts, Glossic Natraqualfs, Oxyaquic Glossudalfs, Oxyaquic Eutrudepts, Aquic Glossudalfs, and Vertie Hapludalfs. Drainage classification ranged from well-drained to somewhat poorly drained, with Lovelady classified as well-drained. Hickory Creek soils were 54.3% Inceptisols, with Alfisols at 38.4%. Laneville soil series (Fluvaquentic Eutrudept) was the most abundant at 34.8% land coverage. The remaining soils were Vertie Hapludalfs, Fluvaquentic Dystrudepts, Aquic Glossudalfs, Fluvaquentic Endoaquepts, Glossic Paleudalfs, and Arenic Hapludults. Like Arbor Grove, drainage classification ranged from well-drained to somewhat poorly drained; moderately well-drained soils were the most abundant, including Laneville loam. Over 70% of soils at Atoy were Ultisols, with Sacul fine sandy loam (Aquic Hapludult) covered the majority (55.1%). The predominant drainage classification was moderately well-drained covering 72% of the property.

Experimental design and sampling

Three trees from each site were sampled in 2018, for both above and below-ground biomasses, to evaluate possible aboveground predictors for belowground biomass. Soils were sampled in 2003 and 2015 for soil organic carbon to evaluate if any significant change had occurred. Aboveground biomass was defined as all biomass >5 cm above ground level. Basal area and number of trees ha-1 were determined by using a 10 m radius, circular sample plot centered on the sample tree.

Sample trees were cut at ground line; Diameter at Breast Height (DBH) was recorded prior to tree felling. Once felled, two limbs from the upper and two from the lower crown were randomly selected, separated into branch and needle components, dried and weighed to develop a correction for moisture content. The remainder of crown green weight biomass was weighed using an electronic platform scale in the field and recorded to the nearest 0.01 km. Necromass was separated from biomass in order to avoid over estimation of biomass. The merchantable length (between 5 cm above ground line to a 5 cm diameter top) of each stem was measured and cut into manageable segments for weighing. Mass lost to kerf during cutting was assumed to be negligible. Stems were weighed and recorded to the nearest 0.01 km. Three sub samples were cut from the stem; one at breast height, one at one-half of merchantable stem height and one at 90% merchantable stem height, and were oven-dried and weighed to develop a correction for stem moisture content. Moisture lost in stem and crown samples between the time of sampling and initial weighing was assumed to be negligible. Sub-samples were weighed, and then placed in a forced draft drying oven at 60°C until a constant weight was achieved and then recorded.

Destructive sampling was employed to sample belowground biomass; however significant effort was made to keep roots intact to minimize root biomass loss. A combination of an air spade (between 90 and 100 psi), and mini excavator was used in order to extract coarse roots, stumps and taproots. For coarse roots, a one m^2 sample area was randomly selected along an imaginary grid system with grid center on the stump. Using the mini excavator, a trench was dug parallel and adjacent to one side of the sample. Using the air spade, the 1 m^2 area was excavated in 20 cm depth increments to one m depth and all coarse roots collected. A visual inspection of roots in the field was used to distinguish loblolly pine roots from other roots based on physical and morphological characteristics. Coarse root samples were then oven-dried until a constant weight was achieved. Sub-samples were taken from coarse roots and cleaned of remaining soil to develop a correction value for remaining adhering soil mass. Coarse roots were scaled to the 10 m radius plot used in calculating basal area and subsequently divided by the number of trees per plot to determine the average contribution of individual trees to carbon stored in coarse roots.

Pine taproots were defined as roots greater than 2 mm in diameter originating from the primary root ball with a vertical orientation. Removal of the stump and taproot system began by excavating a "Y" shaped trench, with the stump and assumed diameter of the taproot system between the two arms of the "Y". The air spade was used to remove remaining soil around the taproot system. Determinations were made in the field to continue excavation with the air spade or excavator until the full length of the roots were reached. Once the taproots were fully removed, excess soil was removed using the air spade and non-taproots were removed. The entire taproot system was then weighed and three sub-samples were cut from the most prominent taproot and used to correct for remaining soil and moisture content. Sub-samples of the tap roots were collected near the end of the tap root, the middle, and the upper portion of the root.

Soil samples were collected to a depth of 40 cm on a 1.7 ha grid in 2003 and 2015, and analyzed in the Soil Plant and Water Analysis Laboratory (SPWAL) located at Stephen F. Austin State University for organic carbon content. Excess soil not used in analysis was oven-dried at 60°C and stored at 22°C.

Carbon content of samples collected in 2003 was measured using different analytical equipment than was used for samples collected in 2015. To determine if there was error caused by machine differences that could be misinterpreted as a difference in soil organic carbon, 16 randomly selected samples from 2003 were reanalyzed. It was assumed that after the initial drying and storage, carbon mineralization was negligible.

In 2015, the O horizons were sampled from a 27 cm diameter plot on the same 1.7 ha grid from which soil were sampled, and oven-dried at 60°C until a constant weight was achieved. Organic matter was determined on subsamples by the loss on ignition method in a muffle furnace at 500°C. The organic matter concentration was converted to organic carbon by dividing organic matter mass by 2.

Statistical analysis

Using paired t-tests, the average SOC in the mineral portion of the soil was compared by site between 2003 and 2015. To determine outliers in the data set, Tukey's determination of outliers was used. Initial O horizon and coarse woody tree roots were assumed to be negligible due to the previous grass-only vegetation community present before tree planting. Prior to tree planting there was no significant accumulation of organic litter in an O horizon. Correlation analysis was performed on all variables to determine if any aboveground variable (DBH, stem height, stem mass, and crown mass) was correlated with carbon stored belowground in coarse woody roots and taproot systems. Regression analysis was performed on significant correlations to develop models for estimating belowground carbon in coarse woody roots using measured aboveground variables. SAS version 9.4 software was used to perform all statistical analysis at the alpha value of 0.05.

RESULTS AND DISCUSSION

Belowground carbon

To account for any differences in the laboratory's ability to quantify soil organic carbon due to equipment changes between measurement years, a linear transformation was applied to the original values reported in 2003. After the linear transformation (equation 1) was applied, there were no significant difference between original sample values and the re-analyzed samples; it was assumed that the coefficient of the function represents the actual change in soil organic carbon in samples and the intercept (4043.2) is the difference in the analytical equipment. The differences could be due to changes in calibration technology, hardware and software technologies, or a combination of factors. The adjusted 2003 SOC (CO_3) and the original 2003 SOC (CO_3) readings are both expressed in mg C kg^{1} dry soil.

$CO_3=CO_3+4043.2$ .... (Eq 1)

Soil organic carbon

There was a significant difference between years for mean soil organic carbon ($p<0.0001$), with those in 2017 being consistently higher. No significant differences were detected in SOC in the top 40 cm for Arbor Grove and Atoy (Table 1). Hickory Creek showed a statistically significant increase in carbon in the top 40 cm; this site has poorer drainage than the other two sites as the alluvial floodplain holds more water than soils on the other two sites, which could create more towards anaerobic conditions that may slow the decomposition of soil organic matter.

Site	n	Mean	Standard deviation	± 95% CL	p-value
Arbor Grove	165	-497.6	3385.6	520.5	0.0608
Atoy	150	35.9	4392.2	708.6	0.9203
Hickory Creek	154	3039.7	5399.6	859.6	<0.0001

Table 1: Paired t-tests between Soil Organic Carbon (SOC) between 2003 and 2015 by site in mg C kg^{1} soil (a=0.05)

Course and tap roots

Coarse roots are usually distributed in greater quantities near the stem; yet with the uniformity of stem planting associated plantation monoculture, the excavated areas should be representative of coarse root densities within the stand. In the top 1.0 m, trees at Arbor Grove had 17.58 kg m^{-2} C in coarse roots, Atoy 11.42 kg m^{2} C, and Hickory Creek 14.50 kg m^{-2} C [24]. The lower values at Atoy are believed to be because of higher clay content of Ultisols, which may inhibit root growth.

At all sites, carbon stored in coarse roots in the top 20 cm accounted for over 30% of total carbon stored in coarse roots (Table 2), while root biomass carbon in the top 40 cm accounted for the majority of carbon stored in lateral coarse roots, with Arbor Grove having the lowest proportion at 62.4%. The 0 to 60 cm soil depths contained over 75% of carbon stored in coarse woody root biomass for all sites, in contrast to found 70%-75% of loblolly pine lateral roots located in the top 20 cm; the latter study was located on sandy loam over sandy clay to clay subsoils, similar to the soils in this study. Loblolly pine genetics in the Lost Pines region of Texas and Atlantic Coast Pines of the Piedmont region in North Carolina did not play a part in lateral root partitioning by depth, with similar results to [14]. Trees excavated by were 16 years old when excavated and trees excavated by were four years old. Additionally, conducted their study on sandy, siliceous, thermic Psammentic Hapludults, while excavations at the Atoy site were conducted on fine, mixed, active, thermic Aguie Hapludults. Coarse roots at Atoy were observed in greater depths compared to, suggesting that age plays a part in coarse root partitioning [25].

Depth (cm)	Arbor Grove	Atoy	Hickory Creek
0-20	32.6	38.3	38.1
20-40	62.4	71.8	78.5
40-60	75.9	85.9	92.6
60-80	92.5	98	98.3
80-100	100	100	100

Table 2: Cumulative percentage of total carbon by depth to 100 cm in coarse woody roots (excluding tap root systems) by site.

For Hickory Creek, coarse roots increased at depths of 20-40 cm, while Arbor Grove experienced an increase at 60-80 cm in depth. Only Atoy displayed a decline in coarse roots concentrations at every depth interval (Table 3). The Bt horizons associated with the Aquic Hapludult (Sacul fine sandy loam) has a higher mechanical resistance with depth, which may cause a greater diminishing return for trees to increase rooting density at greater depths. There were an insignificant number of coarse roots below 100 cm in relation to roots above 100 cm in depth. Excavated tap root systems had means of 25.75 kg C tree^{-1}, 32.10 kg C tree^{-1}, and 34.83 kg C tree^{-1} for Arbor Grove, Atoy, and Hickory Creek, respectively. Mean tap root system C, expanded to per area basis was 10.17, 13.28, and 18.33 Mg C ha^{-1}, respectively for Arbor Grove, Atoy, and Hickory Creek.

Depth (cm)	Arbor Grove	Atoy	Hickory Creek
0-20	61.2	43.6	52.7
20-40	52.4	38.4	60.5
40-60	23.9	20.9	22.1
60-80	26.7	13.8	8.1
80-100	12.8	2.3	3.1

Table 3: Mean Kg C sequestered in coarse roots by depth by site.

O horizons

Mean C in the 0 horizons were 6.56 Mg C ha^{-1}, 6.28 Mg C ha^{-1}, and 6.48 Mg C ha^{-1} for Arbor Grove, Atoy, and Hickory Creek, respectively (Table 4), showing that loblolly pine contributed significantly to accumulation of O horizon carbon. While carbon stored in the O horizon is subject to more rapid decomposition relative to other C sinks in forested systems, barring drastic changes in the system (e.g. fire, removal, clear cutting, etc.) decomposition and mineralization rates will not outpace accumulation rates of the 0 horizon. The system may shift over time with less accumulation and higher decomposition rates, but on a decadal scale, carbon will still be present in organic form within the O horizon.

Source	Arbor grove	Atoy	Hickory creek
SOC	-	-	14.59
O Horizon	6.56	6.28	6.48
Coarse roots	6.43	4.72	7.18
Tap roots	10.17	13.28	18.33
Total	23.16	24.28	46.58

Table 4: Belowground carbon and O horizon carbon by site (Mg ha-1).

Carbon sequestration

Hickory Creek was the only site that had a statistically significant change in SOC from 2003 to 2015. The grassland ecosystems present prior to planting likely had carbon sequestered primarily in SOC, with the negligible latency of carbon sequestered in biomass due to the rapid decomposition associated with non-woody root structure of grasses. From 2003 to 2015, the Arbor Grove and Atoy sites had no significant difference in carbon stored in SOC, therefore only carbon stored in coarse roots and tap root systems contributed to carbon sequestered. The Arbor Grove site sequestered 16.60 Mg C ha^{-1} and Atoy sequestered 18.01 Mg C ha^{-1}. Hickory Creek had an increase in carbon stored in SOC with 14.59 Mg C ha^{-1} sequestered, and with the addition of coarse roots and tap root systems, sequestered 40.10 Mg C ha^{-1} (Table 5).

Source	Arbor Grove	Atoy	Hickory creek
SOC	-	-	14.59
O Horizon	6.56	6.28	6.48
Coarse roots	6.43	4.72	7.18
Tap roots	10.17	13.28	18.33
Total	23.16	24.28	46.58

Table 5: Net Carbon sequestered (Mg ha^{-1}) below ground by site.

The largest contributor to carbon sequestered belowground on all sites were tap roots, with coarse roots contributing the least. Net carbon sequestered in SOC at Hickory Creek was another large contributor to total carbon sequestration on that site. However, the Arbor Grove and the Atoy sites are reported to contain less total carbon sequestered belowground due to the lack of a change in carbon stored in SOM. The difference of SOC present in 2015 from 2003 at the Hickory Creek site significantly contributed to total belowground carbon sequestered compared to the other two sites (Table 5).

In addition to sequestering the most carbon, Hickory Creek also had the most carbon present belowground (Table 5). With the sites being in close proximity, the difference is most likely due to pedologic differences. At all sites, carbon present in SOC made up over 70% of total belowground carbon, with Atoy having the highest proportion of carbon in SOC to total belowground carbon (Table 6). The proportion of carbon stored by SOC, coarse roots, and tap roots were similar, differing only by 2.01 percentage points between carbon stored in coarse roots between Atoy and Arbor Grove. The O horizon sequestered over 6 Mg C ha-1 of additional carbon on all sites (Table 4).

Source	Arbor grove	Atoy	Hickory creek
SOC	52.07 (75.82)	62.79 (77.71)	65.79 (72.05)
Coarse roots	6.43 (9.36)	4.73 (5.85)	7.18 (7.86)
Tap roots	10.17 (14.80)	13.28 (16.43)	18.33 (20.07)
Total	68.67	80.8	91.3

Table 6: Belowground carbon (Mg ha^{-1}) in 2017. Values in parenthesis are percent (%) total carbon belowground by site.

Total Aboveground and Belowground C variables were:

Aboveground C=Crown C + Stem C,

Belowground C=Tap root C + Coarse root C,

Total tree C=Aboveground C + Belowground C.

All values were expressed in kg C tree^{-1} with the exception of DBH and stem height, which were expressed in cm. The most significant correlation was between belowground carbon and carbon sequestered in tap roots. However, this relationship does not provide a suitable means of predicting belowground carbon sequestered in coarse roots. The correlation analysis did reveal that total carbon sequestered in trees was correlated with carbon sequestered in stems with an r value of 0.9455. Linear regression analysis was performed on carbon sequestered in merchantable stems and total tree carbon sequestered (equation 2), with a p-value<0.0001, r^2=0.8940, and an RMSE=12.8054.

Total C=74.6618 + 1.1350 (Stem C) .... (Eq 2)

Where Total C is the total carbon sequestered in loblolly pine biomass (above-and below-ground) and Stem C is the carbon sequestered in loblolly pine merchantable stems. While not a direct predictor for carbon sequestered belowground in coarse root mass, equation 2 estimates total carbon sequestered, which is more applicable and relevant to practicing natural resource managers. However, carbon in merchantable stems is not typically a metric that managers have readily available. Because producers are focused on predicting merchantable volume, the majority of the models used to predict merchantable volume use DBH and stem length in calculations. Additionally, DBH and stem length (tree height) are easily, and commonly, measured in the field.

In order to produce a meaningful model for managers to assess carbon sequestered in loblolly pine biomass, a nonlinear regression was performed using DBH and merchantable stem length as input parameters, resulting in equation 3, with a RMSE=12.8475:

Total C=0.048 × $DBH^{1.1241}$ × $SL^{0.6415}$ .... (Eq 3)

Where Total C is the total carbon sequestered in loblolly pine biomass, DBH is the diameter at breast height in cm, and SL is the merchantable stem length in cm. Equation 3 offers a more standard approach to estimating total carbon sequestered by using parameters commonly measured in forest inventories; DBH and merchantable stem length. In comparison, equation 2 requires the user to calculate carbon sequestered in stems to then calculate total carbon sequestered. Equation 3 allows the direct calculation of carbon sequestered, both above and below-ground per tree, directly from direct tree measurements.

CONCLUSION

All sites had an increase in carbon sequestered belowground, with increases in carbon stored in tap roots, coarse roots, and O horizons, but only Hickory Creek experienced a significant increase in SOC. Coarse roots biomass were greater at deeper depths, on all sites, than reported in previous studies, with over 75% of carbon stored in coarse roots found between 0 and 60 cm. O horizons on all sites sequestered significant amounts of carbon. The latency of these horizons, and the carbon within them, is heavily dependent on management practices. SOC in loblolly pine plantations is dependent on many soil factors, with only one site having a statistically positive net sequestration of carbon. More research into soil parameters affecting the accumulation of SOC in loblolly pine plantations is needed in order to more accurately assess whether afforestation leads to an increase in SOC in loblolly pine plantations.

Using regression analysis, two equations were developed using aboveground variables to estimate total carbon sequestered by loblolly pine. Derived from linear regression, equation 2 uses carbon sequestered in merchantable loblolly pine stems to calculate total carbon sequestered in total loblolly pine biomass. Equation 3, derived from nonlinear regression techniques, uses DBH and merchantable height to calculate total carbon sequestered in loblolly pine biomass. Equation 3 was developed to be more useful in real-world applications by using parameters that are commonly measured during forest inventories; in contrast, carbon in stems, which cannot directly be calculated from field measurements, requires the use of additional equations to estimate above-ground carbon.

With all trees being 16 years in their first rotation with a resulting narrow range in DBH, future studies should examine trees on a wider age range, as well as different soils, to determine whether relationships are constant across age ranges and different soil conditions such as texture and drainage class.

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AUTHOR CONTRIBUTIONS

Ken Farrish, Jason Grogan, Brian Oswald and Frantisek Majs contributed to the study design. William Wedge was responsible for all data collection and analysis. Brian Oswald and Jason Grogan contributed to manuscript preparation. All Authors have approved the final manuscript.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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