Scientific Research Publishing

Open Journal of Forestry, 2025, 15(3), 210-225
https://www.scirp.org/journal/ojf
ISSN Online: 2163-0437
ISSN Print: 2163-0429

Estimating Aboveground Carbon Stock and Sequestration Potential of Oak-Gum-Cypress Forests on Bottomland Hardwood Sites

Suchana Aryal[1], T. Eric McConnell[2*]

[1]Department of Forest Engineering, Resources & Management, Oregon State University, Corvallis, OR, USA
[2]Department of Forestry, Mississippi State University, Mississippi State, MS, USA
Email: suchana.aryal@oregonstate.edu, *eric.mcconnell@msstate.edu

How to cite this paper: Aryal, S., & McConnell, T. E. (2025). Estimating Aboveground Carbon Stock and Sequestration Potential of Oak-Gum-Cypress Forests on Bottomland Hardwood Sites. *Open Journal of Forestry, 15,* 210-225.
https://doi.org/10.4236/ojf.2025.153012

Received: April 21, 2025
Accepted: July 5, 2025
Published: July 8, 2025

Abstract

An aboveground, whole stand, carbon stock model was constructed for the bottomland hardwood (BLH) oak-gum-cypress forests along the US Gulf Coast and lower Mississippi River Delta region, and the sequestration potential was explored utilizing USDA Forest Service Forest Inventory and Analysis (FIA) plot, condition, and tree data. Carbon stock model predictors were site index, stand age, and basal area. Sequestration was based on basal area increment. Stand age averaged 56.5 years, with 67.4 tonnes/ha of carbon stock on BLH sites on sweetgum site index 21.8 sites. At the 2020 social cost of carbon (\$190 per tonne CO_2e) and a discount rate of 2.00%, the accumulated present value of carbon ranged from \$6500 per hectare over 5 years to \$28,100 per hectare over 35 years. Accumulated present values discounted at 5.00% using potential market prices ranging from \$1.00 to \$50 per ton CO_2e varied from \$31.40 per hectare for 5 years to \$5000 per hectare for 35 years. Findings suggest a revenue stream on BLH sites competitive with other forest-based cash flows.

Keywords

Biomass, Growth and Yield, Timberland, US South

1. Introduction

The role of forests in solving the global concern of greenhouse gas (GHG) emissions and associated global warming was acknowledged by adopting the Kyoto Protocol in 1997. Under the Protocol, over 160 countries, including the US, pledged to keep their GHG emissions below 1990 levels (Barrett, 1998). To achieve this goal, large emitters either become more energy-efficient or purchase carbon offsets (Ribera et al., 2009). As a result, carbon sequestration through forestry practices has emerged as a cost-effective way of reducing emissions for the emitters (Griscom et al., 2017). It has long been counted as a potential mitigation strategy for the ongoing climate change phenomenon. In the United States, the US Environmental Protection Agency (USEPA) has been monitoring GHG emissions since the early 1990s and their latest report shows that US forests stored 61 billion tonnes of carbon in 2021 (Hoover & Riddle, 2022). These data demonstrate the significant role that US forests could play in achieving long-term climate change goals.

In the US, approximately 16% of the nation's annual carbon dioxide (CO_2) emissions are absorbed by the 310 million hectares of existing forestlands (Durkeay & Schultz, 2016). Further, 30% of total forestland in the US is occupied by southern forests, which are expected to sequester 13% of regional GHG emissions (Han et al., 2007). Growing wood and harvested wood products offset from 12% to 19% of the country's fossil fuel emissions in the US (McKinley et al., 2010). More than 700 million tonnes of CO_2 equivalent (tCO_2e) per year is required for that offset, of which 363 million tCO_2e is contributed by productive southern forests (Galik et al., 2013). Among the various forest carbon sinks, bottomland hardwood (BLH) forests found along river floodplains and coastal plains have been identified as important sinks for carbon sequestration in the south (Shoch et al., 2009).

The BLH forests are extensively found in the Lower Mississippi Alluvial Valley (LMAV) but also dominate floodplains along the Gulf and Atlantic coastal plains (Wharton et al., 1982). Historically, the LMAV supported roughly 10 million hectares of productive BLH forests, of which only about 2.70 million hectares were intact by the 1980s, showing around a 75% decline in the area from historical values (King et al., 2006). This has led to a loss of carbon storage capacity (Wigginton et al., 2000) and a release of stored carbon back into the atmosphere (Hendrickson, 2003). Over the decades, the total hectareage of BLH forests in the southeastern US (the greatest of which lies within the LMAV) has increased as the result of reforestation activities, federal incentives, and management approaches (King et al., 2006). However, the long-term success of restoration efforts is still uncertain. Carbon markets could be one potential tool encouraging conservation and contributing to managing BLH forests by providing a financial incentive for holding onto these forests.

Some earlier domestic carbon market approaches in the US included the cap-and-trade program, Regional Greenhouse Gas Initiative (RGGI), and California Climate Action (Malmsheimer et al., 2008). The first and largest voluntary carbon market was Chicago Climate Exchange (CCX; Gans & Hintermann, 2013), followed by other voluntary markets, including the American Carbon Registry (ACR), Climate Action Reserve (CAR), and Verified Carbon Standards (VCS; Galik et al., 2013). In addition, programs like Blue Source, Working Woodland, and

Finite Carbon allow landowner involvement but require more significant ownership and extended commitment periods (Tanger & Norman, 2022), while short-term agreements like NCX offered flexibility, reduced financial risk and cost-effectiveness to small landowners (Sedjo & Marland, 2003). Despite these market approaches, developing carbon offset projects in BLH forests face several challenges, including more accurate quantification of carbon sequestration potential in BLH sites. This study seeks to improve our understanding of aboveground live tree carbon stocks and the sequestration potential of BLH forests through the development and application of growth and yield modeling techniques.

The Forest Vegetation Simulator (FVS), a widely used forest growth and yield modeling tool for carbon estimation in the US, comes with 20 geographic variants (Dixon, 2002) and is the official tool for growth projection on national forest holdings (Shaw, 2009). However, the plot data utilized in this study to model carbon stock and estimate the sequestration potential were obtained from both private and public forest lands. In addition, although naturally regenerated stands cover a significant portion of BLH forests in the LMAV, much of the published work has focused on afforested stands and plantation forests (Moerschbaecher et al., 2016). A stand-level carbon stock model for naturally regenerated oak-gum-cypress forests on BLH sites was developed to address this research gap using 403 FIA sample plots. Furthermore, the sequestration potential was estimated under different management scenarios (thinning and regeneration harvest). The development models aimed to provide BLH forest landowners, managers, and investors with information on aboveground forest carbon content. This could help them make informed forest management decisions and take advantage of the growing carbon market as a significant source of financial support.

2. Methods

2.1. Study Area and Data

Primary data were obtained from the USDA Forest Service's Forest Inventory and Analysis database, collected by the Southern FIA unit. The FIA study locations selected represented BLH sites, and plots were chosen based on the criteria to obtain oak-gum-cypress forests in naturally regenerating conditions. Condition, plot, and tree tables for the BLH permanent plots in Alabama, Arkansas, Louisiana, Mississippi, two eastern Texas units, and one unit in western Tennessee (**Figure 1**) were downloaded from the FIA database and were then merged individually into Microsoft Excel. The data were queried for the most recent seven years of plots surveyed. They were next filtered according to the following criteria: oak-gum-cypress as the primary forest type (which resided on both narrow and wide floodplains and bottomlands), natural origin, live trees of growing stock size (at least 11.7 cm diameter at breast height), land not permanently underwater or in the presence of ridges and gullies (excluding inoperable lands), no record of past silvicultural treatments (natural disturbance included), stand age at least 20 years but no more than 100 years, and growing stock basal area of at least 13.8 m^2/ha, which was considered a threshold of full stocking (Schultz et al., 2010). Lastly, we calculated a stand density index ratio, which was the sum of individual trees' SDI relative to the plot's SDI at its quadratic mean diameter, and set a minimum threshold of 0.90 to better achieve an even-aged condition (Shaw & Long, 2007). Based on these criteria, a total of 403 sample plots were identified (**Figure 1**). Site index for the plots was set using an equation for sweetgum (*Liquidambar styraciflua*) for all resident plot trees and averaged arithmetically at the plot level (Carmean et al., 1989; Walters & Ek, 1993). Aboveground oven-dry biomass weight was the whole of three components, the tree stem, branches, and foliage (Schultz et al., 2013). The above ground carbon content was assumed to be 50%. These were calculated for the plot and expanded to a per hectare basis using the trees per hectare expansion factor. Plots were divided into model building and testing sets randomly at a 9:1 ratio.

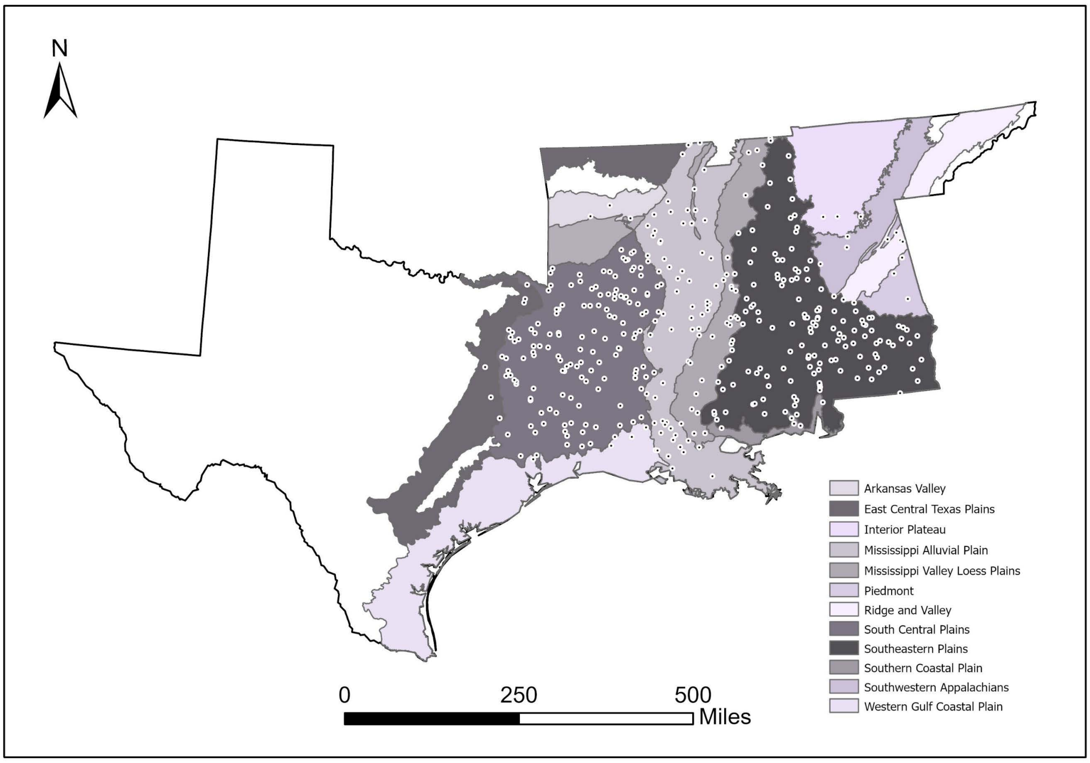

Figure 1. USDA Forest Service Forest Inventory and Analysis survey locations for naturally regenerated bottomland hardwood oak-gum-cypress forest type in six states across twelve USEPA level III ecoregions.

2.2. Estimating Whole Stand Carbon Stock and Sequestration

The carbon stock/yield model's functional form followed Smith et al. (1975), when they modeled hardwood yields across a range of sites. Sullivan et al. (1983) also used this model form for modeling oak-gum stands in central Mississippi minor stream bottoms

$$\ln C = \alpha_0 + \alpha_1 \ln(S) A^{-1} + \alpha_2 A^{-1} + \alpha_3 \ln(B) + \sum_{j=1}^{11} \gamma_i D_i + \varepsilon \quad (1)$$

where ln was the natural logarithm; C was the dependent variable (carbon stock, tonnes per hectare, as one-half dry biomass weight); S was the plot average sweetgum site index (base age 50 years in meter) calculated using Carmean et al. (1989); A was stand age (years); and B was growing stock basal area (m^2/ha); α_i were parameters for $\ln(S)A^{-1}$, A^{-1}, and $\ln(B)$; γ_j were parameters for eleven ecoregion dummy variables for n = 403 study plots (**Figure 1**) with the East Central Texas Plains being the reference group (United States Environmental Protection Agency, 2017); and ε was the error term. Predicting growth (sequestration) required first constructing a companion basal area equation, which was differentiated with respect to age. Doing so accounted for both growth and mortality as stands progress from many small trees to fewer larger ones (Buckman, 1962).

The basal area model was

$$\ln B = \beta_0 + \beta_1 \ln(S) A^{-1} + b\beta_2 A^{-1} + \beta_3 \ln(N) + \varepsilon \quad (2),$$

where N was growing stock trees per hectare (TPH), β_i were parameters, and all other variables being as previously described (Equation (1)). The first derivative of basal area with respect to age defined the annual growth rate

$$dB = \hat{B}\left(-b_1 \ln(S) A^{-2} - b_2 A^{-2}\right) dA \quad (3),$$

with dB being the difference in basal area; $\hat{B}$ was predicted arithmetic mean basal area per hectare adjusted by the model's correction factor for a particular tract's site index, age, and trees per hectare from Equation (2); b_i were regression coefficients from Equation (2); and dA was the difference in age. Specifying the derivative with respect to age reduced N to a constant, and the derivative of a constant is zero. Basal area growth therefore occurred at the same rate for all sites' numbers of trees per hectare. Basal area increment, square meter per hectare per year, can be calculated sequentially from the subsequent age $t+1$ to some future time at age T. Future basal area, B_T was

$$B_T = \hat{B} + \left(\sum_{Age_{t+1}}^{T} \hat{B} * dB \right) \quad (4).$$

where predicted arithmetic mean basal area per hectare was added to the sum product of $\hat{B}$ and dB from age $t + 1$ to the end of the desired growth period, T.

Equations (1) and (2) were estimated simultaneously because the correlation of the two models' residuals was significant at alpha = 0.05, albeit low in magnitude (r = 0.44). But Equation (3) also contained basal area as an independent variable, whereas it was the dependent variable in Equation (4). Basal area was therefore endogenous to the system. Together, these elements led to using three-stage least squares via SAS 9.4's SYSLIN procedure at alpha = 0.05 (SAS 2023). Site index and age were exogenous, while trees per hectare served as an instrumental variable that exhibited some correlation with basal area (r = 0.50) but little with carbon stock (r = 0.19). Outliers were identified using standardized residuals with absolute values greater than 2.00 for each equation, removed, and the SYSLIN procedure was rerun. The final equation was evaluated using the validation set to calculate the residuals' average (bias), standard error (precision), mean absolute deviation (MAD), mean absolute percent error (MAPE). A correction factor of $MSE/2$ accounted for the bias introduced by the transformation (Baskerville, 1972). After model training and testing were completed, the two datasets were merged to discover the model's final coefficients. Equations (3) and (4) were calculated in MS Excel with the PROC SYSLIN results.

2.3. Discounted Accumulated Present Carbon Value

Future carbon sequestration per acre was evaluated for a typical stand of average quality at the study means for stand age (rounded to age 56), site index (rounded to 22), and TPH (rounded to 250). A predicted basal area per acre $\hat{B}$ was found per Equation (2). The average values for age, site index, and $\hat{B}$ were input into Equation (1) to next provide the initial carbon stock. The stand was then plotted onto the southern bottomland hardwood stocking guide from Goelz (1995). It was assumed the stand would experience 10% mortality to grow in basal area per acre to reach 100% stocking for a timber harvest using our basal area growth equation and the USDA Forest Service's mortality and growth data for our study region. The needed future basal area $\hat{B}_T$ to reach 100% stocking at 225 TPH was 28.6 m^2/ha (Goelz, 1995). Future basal areas were determined from age 56 years to the stand age A_T needed to achieve 28.6 m^2/ha, which was $A_T = 92$ years. The future basal areas were exported back to Equation (1) sequentially to calculate each year's future carbon stock per hectare. The year-on-year changes in the per hectare carbon stock represented the tonnes of carbon sequestered per hectare over the holding period. The carbon captured was considered eligible for payment up to age A_{T-1}, which was 91 years.

Discounted accumulated present carbon values (APCV) were calculated from two perspectives. The first was as a social value. The formula was

$$APCV, \frac{\$}{ha} = P * \sum_{t=1}^{35} \left(\frac{3.6667 * \Delta\hat{C}_{ha}}{e^{rt}} \right), \quad (5),$$

with $P = \$190$ per tCO_2e (\$172.37 per ton for emission year 2020) being the social value of carbon (US EPA, 2023), $\Delta\hat{C}_{ha}$ was the carbon sequestered per hectare per year. The carbon sequestered each year was converted to tCO_2e using a multiplier of 3.6667, which equals the atomic weight of carbon dioxide (44) relative to the atomic weight of carbon (12). The denominator was comprised of the base of the natural logarithm e, the social discount r of 2.00%, and t was the sequential number of years ($t = 1, 2, 3, \ldots, 35$) from age 56 to age A_{T-1} = age 91. The social cost of greenhouse gas emissions is, "…a comprehensive metric that includes the value of all future climate change impacts (both negative and positive), including changes in net agricultural productivity, human health effects, property damage from increased flood risk, changes in the frequency and severity of natural disasters, disruption of energy systems, risk of conflict, environmental migration, and the value of ecosystem services" (US EPA, 2023). Conversely then, the APCV provides a social net present benefit metric for removing tCO_2e from the atmosphere and sequestering the carbon in trees.

Discounting the sequestered carbon followed Lundgren's (1966) calculation of expectation value index, which allowed a range of potential market prices to be studied. The market value of carbon followed Equation (5), with P representing prices of \$1.00, \$5.00, \$10.00, \$25.00, and \$50.00 per tCO_2e. A discount rate more typical of forest investments was set at r = 5.00%. Both the social and market APCVs were calculated for lengths of t = 5 years to t = 35 years from the present in 5-year intervals. Annual equivalent values (AEV) were calculated at each contract length, so all could be compared on an equal time scale

$$AEV, \frac{\frac{\$}{ha}}{yr} = APCV * \left(\frac{re^{rt}}{e^{rt} - 1} \right) \quad (6).$$

3. Results

Table 1 provides summary statistics for the FIA study plots for the dependent and independent variables used. The overall carbon stock ranged from 12.4 to 258.3 tonnes/ha and averaged 67.4 tonnes/ha. The study plots averaged 56.5 years of age, a basal area of 18.6 m^2/ha, with 250 trees/ha. Mean sweetgum site index was 71.6 feet at base age of 50 years. The mean was pulled to the right of the median for the variables.

Table 1. Per hectare descriptive statistics of USDA Forest Service oak-gum-cypress bottomland hardwood plots used in the study, n = 403. Plots were located within the states of Alabama, Arkansas, Louisiana, and Mississippi, along with portions of Tennessee (western) and Texas (eastern).

Statistic	Forest Measurements				
	Site Index, m at 50 yr	Stand Age, yr	Growing Stock Basal Are m^2/ha	Growing Stock Trees per hectare	Carbon stock, tonnes per hectare
Mean	21.8	56.5	18.6	250.6	67.4
Standard Deviation	3.98	17.9	9.75	137.0	45.9
Median	21.4	60.0	16.3	208.2	53.8
Minimum	11.2	20.0	5.63	29.7	12.4
Range	27.0	80.0	60.3	728.7	245.9
Maximum	38.2	100.0	65.9	758.4	258.3

3.1. Simultaneous Model Estimation

The initial model was run using Equations (1) and (2), and the generated data visualizations found the assumptions regarding the residuals were met. Twenty-eight outliers were identified, removed, and the model was refit. The variables site index, age, and basal area were all significant in the carbon model, but none of the ecoregions significantly differed. The ecoregions were then dropped from Equation (1), the outliers were returned to the dataset and the model was reconstructed. Twenty-eight total outliers were again detected and isolated.

The model development set revealed anticipated positive marginal effects of $\ln(S)A^{-1}$ and $\ln(B)$ on carbon yield and a negative marginal effect of A^{-1}. The adjusted coefficient of determination was 0.8922. Assessing the model using the validation dataset found mean bias was 0.67 tonnes/ha with a standard error of 14.68; on percentage bases these were −0.08% and 23.0% respectively. The MAD was 9.21 tonnes/ha, and the MAPE was 3.04%. The basal area prediction model's coefficients were all significant at α = 0.05 with the expected signs. The adjusted R-square was 0.6021. Validation metrics for the basal area model included a mean bias of 0.59 m^2/ha (−0.62%) with a standard error of 1.21 (18.8%). The MAD was 4.75 m^2/ha, and the MAPE was 24.7%.

The full dataset was then run to find the final coefficients, and those results can be found in Table 2 for the carbon stock and Table 3 for basal area. Thirty outliers were identified and removed. The adjusted R-square increased slightly for both carbon (adj $R^2 = 0.9019$) and basal area (adj $R^2 = 0.6364$). Other supporting statistics, model mean square error, analysis of variance table F and p values, and correction factor are also provided for each model. All coefficients were significantly below the 0.01 level with expected signs. The derivative of the basal area equation from Table 3 was

$$dB = \hat{B}\left(243.1A^{-2} - 61.5\ln(S)A^{-2}\right)dA \quad (7).$$

Table 2. Parameter estimates and model summary of carbon stock model for bottomland oak-gum-cypress forests along the US Gulf Coast and Mississippi River delta region. A = stand age, S = sweetgum site index (meters at base age 50 years), B = basal area per hectare.

Predictor	Statistics			
	Coefficient	Standard error	t-value	P value
Intercept	2.4427	0.0931	26.25	<0.0001
$\ln(S)A^{-1}$	53.9560	2.7933	19.32	<0.0001
A^{-1}	−208.4710	9.8962	−20.65	<0.0001
Ln(B)	0.8569	0.0261	32.89	<0.0001

Adjusted R square = 0.9019; Model Mean Square Error = 0.0260; F = 1141.60; $p < 0.0001$; Correction Factor = 1.0131.

Table 3. Parameter estimates and summary statistics of the basal area model for bottomland oak-gum-cypress forests along the US gulf coast and Mississippi River delta region. A = stand age, S = sweetgum site index (meters at base age 50 years), N = number of growing stock trees per hectare.

Predictor	Statistics			
	Coefficient	Standard error	t-value	P value
Intercept	0.3383	0.1457	2.32	0.0208
$\ln(S)A^{-1}$	61.5262	4.5220	13.61	<0.0001
A^{-1}	−316.1960	21.2929	−14.85	<0.0001
Ln(N)	0.6545	0.0293	22.31	<0.0001

Adjusted R square = 0.6364; Model Mean Square Error = 0.0770; F = 218.00; $p < 0.0001$; Correction Factor = 1.0392.

3.2. Carbon Sequestration Scenarios

The stand at an average age of 56 years was 77% stocked (Goelz, 1995). It took 36 years to reach 100% stocking for a timber harvest. Carbon thus accumulated for 35 years to age 91 years. Carbon accumulation came to 9.91 tonnes/ha over the first five years and was 54.9 tonnes/ha over 35 years (**Table 4**). Carbon sequestration provided $6507 per hectare in social APCV in the first five years. By 20 years, social APCV had surpassed $20,000 per hectare and exceeded $25,000 per hectare in 30 years. Over 35 years, $28,146 per acre in social value had accumulated. The social AEV values ranged from $1118 per hectare per year over 35 years to $1368 per hectare per year over 5 years.

Table 4. Accumulated present social carbon values per hectare (currently valued at $190/tCO₂e at discount rate of 2%) for a fully stocked bottomland oak-gum-cypress stand at 5-year intervals along with the equivalent annual income generated over the respective intervals. Dollar values greater than $1000 are rounded to the nearest whole dollar.

Number of Years	Statistics		
	Carbon Sequestered, tonnes/ha	Accumulated Present Social Value of Carbon	Annual Equivalent Value, $/ha/yr
5	9.91	$6507	$1368
10	19.0	$11,922	$1315
15	27.4	$16,431	$1268
20	35.1	$20,188	$1225
25	42.3	$23,325	$1186
30	48.8	$25,948	$1150
35	54.9	$28,146	$1118

Table 5. Accumulated present carbon market values, dollars per hectare (discounted at a rate of 5%) for a fully stocked bottomland oak-gum-cypress stand at 5-year intervals along with the equivalent annual income generated over the respective intervals. Dollar values $1,000 per hectare and greater are rounded to the nearest dollar. tCO_2e = tonnes carbon dioxide equivalent; AEV = Annual Equivalent Value, dollars per hectare per year.

Number of Years	**Revenues**									
	$1/ tCO_2e	**AEV**	**$5/ tCO_2e**	**AEV**	**$10/ tCO_2e**	**AEV**	**$25/ tCO_2e**	**AEV**	**$50/ tCO_2e**	**AEV**
5	$31.40	$7.10	$156.99	$35.49	$313.98	$70.97	$784.95	$177.43	$1570	$354.86
10	$53.89	$6.85	$269.45	$34.24	$538.90	$68.48	$1347	$171.20	$2695	$342.40
15	$70.01	$6.63	$350.03	$33.17	$700.07	$66.34	$1750	$165.85	$3500	$331.70
20	$81.57	$6.45	$407.84	$32.26	$815.68	$64.52	$2039	$161.30	$4078	$322.59
25	$89.89	$6.30	$449.37	$31.49	$898.74	$62.98	$2247	$157.45	$4494	$314.91
30	$95.85	$6.17	$479.26	$30.85	$958.52	$61.69	$2396	$154.23	$4793	$308.46
35	$100.16	$6.06	$500.82	$30.31	$1002	$60.62	$2504	$151.54	$5008	$303.08

The market-based APCVs ranged from $31.40 per hectare for five years when priced at $1.00 per tCO_2e to as much as $5000 per hectare when priced at $50 per tCO_2e for 35 years (**Table 5**). The market APCV surpassed $100 per hectare over

35 years at the lower \$1.00 per tCO_2e price. As much as \$500 per hectare could be earned at \$5.00 per tCO_2e over 35 years. Total earnings surpassed \$1000 per hectare if a landowner received at least \$10 per tCO_2e for 35 years. A 20-year contract paying at least \$25 per tCO_2e would provide just over \$2000 per hectare in present income. At least \$50 per tCO_2e was required to accumulate more than \$3000 per hectare. The overall range of AEV was from \$6.17 per hectare per year over 35 years at \$1.00 per tCO_2e to \$355 per hectare per year over 5 years at \$50 per tCO_2e. The AEV surpassed \$30 per hectare per year if paid at least \$5 per tCO_2e. It exceeded \$60 per hectare per year if paid at least \$10 per tCO_2e. The AEV bettered \$150 per hectare per year if paid at least \$25 per tCO_2e and \$300 per hectare per year if paid at least \$50 per tCO_2e.

4. Discussion

The standard approach for estimating global, regional, plot, and tree-level aboveground biomass and carbon stock is to develop and apply allometric equations (Brown, 1997; Jenkins et al., 2003; Vieilledent et al., 2012). The aboveground biomass in individual tree studies is typically regressed against DBH (Zianis & Mencuccini, 2004). Using the carbon-to-biomass ratio, the estimated biomass is then converted to carbon (Birdsey, 1992). However, several studies have reported the uncertainty associated with using allometric techniques to calculate forest carbon stocks (Chave et al., 2007; Melson et al., 2011; Van Breugel et al., 2011).

Stand age, site index, and basal area influence forest productivity (Johnsen et al., 2013) and hence the forest carbon stock. This study found an average hectare of naturally regenerating oak-gum-cypress forest on BLH sites across the US Gulf South and Mississippi River Delta was 56.5 years of age, possessed a sweetgum site index of 21.8 m at 50 years, contained 18.6 m^2/ha of basal area, and stored 67.4 tonnes of carbon stock. A system of equations was constructed at the stand level using those variables (along with TPH) to predict basal area and carbon stock specific to BLH sites within oak-gum-cypress forests. The results indicated 90.2% of the variability in carbon stock could be explained with these typical whole stand model variables. The effect of stand age on aboveground live tree carbon stock was highly significant finding, which aligned with others (Keeton et al., 2011; Lutz et al., 2018). Carbon accumulated at a progressively slower rate as stands aged. The basal area model captured 63.6% of the variation with stand age, site index, and TPH as predictors. The TPH was the most significant variable here, as it provides a measure of stand density but is exclusive of tree size. As important here was its role as an instrument in the system due to its (albeit weak) correlation with basal area but lack of correlation with carbon yield. The model system ably handled forest stand data withheld from model development.

Shoch et al. (2009) found carbon stored in BLH forests of the northern LMAV between 20 and 90 years of age was greater than the carbon storage tables from Smith et al. (2006) for the South-Central US. Smith et al. (2006) developed carbon yield tables as a function of only stand age. Smith et al.'s (2006) median carbon stock value was 80.9 tonnes per hectare, while our median was 53.8 tonnes of carbon per hectare (average was 67.4 tonnes of carbon per hectare). Smith et al. (2006) included degraded and understocked stands, while we only examined the growing stock residing in fully stocked stands (those with a stocking level from 60% up to 100%). The carbon stock model developed for our study region included only even-aged, fully stocked stands aged 20 to 100 years. These additional filters we believe led to our somewhat lower values. We then considered basal area and site quality as additional factors, which intuitively improved our carbon stock model's goodness of fit over just using age alone. We did not observe any clear pattern of either overprediction or underprediction with the validations data set.

Gonçalves et al. (2021) studied the relationship between ecoregions and soil carbon stocks across the continental US and found that soil carbon stocks varied greatly among different ecoregions. Their study suggested ecoregions play a significant role in controlling the spatial distribution of soil carbon stocks and future carbon dynamics. However, ecoregions were not significant in our study of BLH aboveground live tree carbon in oak-gum-cypress forests. Land capability classifications transcend ecoregion. Timber production as a land use is generally confined to land classes not suited for cultivation, which is from Class 5 and up (USDA Soil Conservation Service, 1961). Variation in aboveground live tree carbon stock due to soil properties was more influenced at the site level within ecoregions, which we captured by including site index. Similarly, the carbon sequestration rate was higher for a higher site index than the lower-quality sites. This result is consistent with previous studies, indicating a positive relationship between site quality and carbon sequestration rate (Huang et al., 2003; Reinikainen et al., 2014).

Shoch et al. (2009) indicated that the financial returns of carbon sequestration alone are insufficient to offset opportunity costs for alternative land uses, for example agricultural rentals on private lands within the LMAV. Therefore, projects entirely supported by carbon finance may be insufficient for BLH private investors and landowners possessing marginal agricultural land to prevent land conversion. Huang et al. (2003) concluded managing forests for carbon can increase revenues and reduce losses, but only if carbon credit markets are available. The AEV findings for carbon sequestration on BLH sites suggest even \$1.00 per tCO_2e provided an offset to per hectare forestland tax rates (Cushing & Newman, 2018). The AEVs at \$5.00 per tCO_2e were competitive with typical annual forest management costs (Forest Landowners Association, 2024). A viable income alternative to leasing hunting rights was provided by AEVs at \$10.00 per tCO_2e (Hussain et al., 2013). Landowners and investors equipped with knowledge such as this can make more informed financial decisions regarding non-timber income options. The study's limitations, such as its focus on a specific forest type and exclusion of other carbon pools and disturbances, should be considered when interpreting the results. Additional accounting should consider carbon emissions from tree mortality and include offset program administrative costs. The APCVs and AEVs should be interpreted conservatively as upper bounds.

These results hold an important implication for timberland's position as a financial asset. The rural areas where timberland resides are often resource rich yet economically poor. Non-timber income such as this can provide a counterbalance to any adverse timber price trend and volatility. Improving timberland's productive value consequently betters the tax base in the short term (Spurlock et al., 2018). Site index at the margin for forest management to be cost effective declines. Active forest management, such as reforestation, release, etc., becomes more financially attractive. Preferred crop trees can be grown in fully stocked stands with optimum growing space over the medium term. Vigorous carbon sequestration would result in additional non-timber income via carbon offset programs that would supplement, and perhaps even compete with, discounted roundwood values under favorable carbon market conditions based on these results.

5. Conclusion

This study sought to address a gap in our understanding of carbon stock dynamics and sequestration potential of BLH forests by focusing on the oak-gum-cypress forest type. The BLH study sites along the US Gulf South and Mississippi River Delta averaged 56.5 years old and 67.4 tonnes of carbon stock per hectare in their aboveground biomass on sweetgum sites of 21.8 feet at base age 50 years. All predictors for the simultaneous basal area and carbon stock equations were highly significant. Findings indicated from 9.91 up to 54.9 tonnes per hectare of carbon could be captured for hypothetical over lengths of 5 to 35 years. The APCV from a social perspective was \$6507 per hectare accruing in 5 years and up to \$28,146 per hectare over 35 years. The annual equivalent benefit to society ranged from \$1118 to \$1368 per hectare per year. A selection of potential market prices revealed APCVs from \$31.40 per hectare for 5 years at \$1.00 per tCO_2e to as much as \$5008 per hectare at \$50 per tCO_2e for 35 years. These values in annual equivalents were competitive with those incurred by nonindustrial private forest landowners.

Acknowledgements

This publication, a contribution of the Forest and Wildlife Research Center, Mississippi State University, was supported by the USDA National Institute of Food and Agriculture, McIntire Stennis project 1025007. Thank you to the editor, associate editor, and peer reviewers for their time.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Barrett, S. (1998). Political Economy of the Kyoto Protocol. *Oxford Review of Economic Policy, 14,* 20-39. https://doi.org/10.1093/oxrep/14.4.20

Baskerville, G. L. (1972). Use of Logarithmic Regression in the Estimation of Plant Biomass.

Canadian Journal of Forest Research, 2, 49-53. https://doi.org/10.1139/x72-009

Birdsey, R. A. (1992). *Carbon Storage and Accumulation in United States Forest Ecosystems*. Gen. Tech. Rep. WO-59, US Department of Agriculture Forest Service, Northeastern Forest Experiment Station. https://doi.org/10.5962/bhl.title.94267

Brown, S. (1997). *Estimating Biomass and Biomass Change of Tropical Forests: A Primer* (Vol. 134). Food and Agriculture Organization.

Buckman, R. E. (1962). *Growth and Yield of Red Pine in Minnesota*. Tech. Bull. No. 1272, US Department of Agriculture Forest Service, Lake States Forest Experiment Station.

Carmean, W. H., Hahn, J. T., & Jacobs, R. D. (1989). *Site Index Curves for Forest Tree Species in the Eastern United States*. Gen. Tech. Rep. NC-128, US Department of Agriculture Forest Service, North Central Forest Experiment Station.

Chave, J., Chust, G., Condit, R., Aguilar, S., Hernandez, A., Lao, S. et al. (2007). Error Propagation and Scaling for Tropical Forest Biomass Estimates. In Y. Malhi, & O. Phillips (Eds.), *Tropical Forests and Global Atmospheric Change* (pp. 155-164). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780198567066.003.0013

Cushing, T. L., & Newman, D. (2018). Analysis of Relative Tax Burden on Nonindustrial Private Forest Landowners in the Southeastern United States. *Journal of Forestry, 116,* 228-235. https://doi.org/10.1093/jofore/fvx013

Dixon, G. E. (2002). *Essential FVS: A User's Guide to the Forest Vegetation Simulator*. Internal Rep., US Department of Agriculture Forest Service, Forest Management Service Center.

Durkeay, J., & Schultz, J. (2016). The Role of Forests in Carbon Sequestration and Storage. In *National Conference of State Legislatures* (2 p). National Conference of State Legislatures.

Forest Landowners Association (2024). *Costs and Trends of Southern Forestry Practices*. https://forestlandowners.com/cost-and-trends-of-southern-forestry-practices/

Galik, C. S., Murray, B. C., & Mercer, D. E. (2013). Where Is the Carbon? Carbon Sequestration Potential from Private Forestland in the Southern United States. *Journal of Forestry, 111,* 17-25. https://doi.org/10.5849/jof.12-055

Gans, W., & Hintermann, B. (2013). Market Effects of Voluntary Climate Action by Firms: Evidence from the Chicago Climate Exchange. *Environmental and Resource Economics, 55,* 291-308. https://doi.org/10.1007/s10640-012-9626-7

Goelz, J. C. G. (1995). A Stocking Guide for Southern Bottomland Hardwoods. *Southern Journal of Applied Forestry, 19,* 103-104. https://doi.org/10.1093/sjaf/19.3.103

Gonçalves, D. R. P., Mishra, U., Wills, S., & Gautam, S. (2021). Regional Environmental Controllers Influence Continental Scale Soil Carbon Stocks and Future Carbon Dynamics. *Scientific Reports, 11,* Article No. 6474. https://doi.org/10.1038/s41598-021-85992-y

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A. et al. (2017). Natural Climate Solutions. *Proceedings of the National Academy of Sciences, 114,* 11645-11650. https://doi.org/10.1073/pnas.1710465114

Han, F. X., Plodinec, M. J., Su, Y., Monts, D. L., & Li, Z. (2007). Terrestrial Carbon Pools in Southeast and South-Central United States. *Climatic Change, 84,* 191-202. https://doi.org/10.1007/s10584-007-9244-5

Hendrickson, O. (2003). Influences of Global Change on Carbon Sequestration by Agricultural and Forest Soils. *Environmental Reviews, 11,* 161-192. https://doi.org/10.1139/a04-001

Hoover, K., & Riddle, A. A. (2022). *U.S. Forest Carbon Data: In Brief. Congressional Research Service*. https://crsreports.congress.gov

Huang, C., Kronrad, G. D., & Cheng, S. D. (2003). Economic Analysis of Sequestering Carbon in Green Ash Forests in the Lower Mississippi River Valley. *The Scientific World Journal, 3,* 731-740. https://doi.org/10.1100/tsw.2003.61

Hussain, A., Munn, I. A., Brashier, J., Jones, W. D., & Henderson, J. E. (2013). Capitalization of Hunting Lease Income into Northern Mississippi Forestland Values. *Land Economics, 89,* 137-153. https://doi.org/10.3368/le.89.1.137

Jenkins, J. C., Chojnacky, D. C., Heath, L. S., & Birdsey, R. A. (2003). National-Scale Biomass Estimators for United States Tree Species. *Forest Science, 49,* 12-35. https://doi.org/10.1093/forestscience/49.1.12

Johnsen, K. H., Keyser, T. L., Butnor, J. R., Gonzalez-Benecke, C. A., Kaczmarek, D. J., Maier, C. A., McCarthy, H., & Sun, G. (2013). Productivity and Carbon Sequestration of Forests in the Southern United States. In *Climate Change Adaptation and Mitigation Management Options: A Guide for Natural Resource Managers in Southern Forest Ecosystems* (pp. 193-248). CRC Press.

Keeton, W. S., Whitman, A. A., McGee, G. C., & Goodale, C. L. (2011). Late-Successional Biomass Development in Northern Hardwood-Conifer Forests of the Northeastern United States. *Forest Science, 57,* 489-505. https://doi.org/10.1093/forestscience/57.6.489

King, S. L., Twedt, D. J., & Wilson, R. R. (2006). The Role of the Wetland Reserve Program in Conservation Efforts in the Mississippi River Alluvial Valley. *Wildlife Society Bulletin, 34,* 914-920. https://doi.org/10.2193/0091-7648(2006)34[914:trotwr]2.0.co;2

Lundgren, A. L. (1966). *Estimating Investment Returns from Growing Red Pine*. Res. Pap. NC-2, US Department of Agriculture Forest Service, North Central Forest Experiment Station.

Lutz, J. A., Furniss, T. J., Johnson, D. J., Davies, S. J., Allen, D., Alonso, A. et al. (2018). Global Importance of Large-Diameter Trees. *Global Ecology and Biogeography, 27,* 849-864. https://doi.org/10.1111/geb.12747

Malmsheimer, R. W., Heffernan, P., Brink, S., Crandall, D., Deneke, F., Galik, C. et al. (2008). Forest Management Solutions for Mitigating Climate Change in the United States. *Journal of Forestry, 106,* 115-117. https://doi.org/10.1093/jof/106.3.115

McKinley, D. C., Ryan, M. G., Birdsey, R. A., Giardina, C. P., Harmon, M. E., Heath, L. S. et al. (2011). A Synthesis of Current Knowledge on Forests and Carbon Storage in the United States. *Ecological Applications, 21,* 1902-1924. https://doi.org/10.1890/10-0697.1

Melson, S. L., Harmon, M. E., Fried, J. S., & Domingo, J. B. (2011). Estimates of Live-Tree Carbon Stores in the Pacific Northwest Are Sensitive to Model Selection. *Carbon Balance and Management, 6,* 1-16. https://doi.org/10.1186/1750-0680-6-2

Moerschbaecher, M. K., Keim, R. F., & Day, J. W. (2016). Estimating Carbon Stocks in Uneven-Aged Bottomland Hardwood Forest Stands in South Louisiana. In *Proceedings of the 18th Biennial Southern Silvicultural Research Conference. E-Gen. Tech. Rep. SRS-212* (Vol. 212, pp. 589-595). US Department of Agriculture, Forest Service, Southern Research Station.

Reinikainen, M., D'Amato, A. W., Bradford, J. B., & Fraver, S. (2014). Influence of Stocking, Site Quality, Stand Age, Low-Severity Canopy Disturbance, and Forest Composition on Sub-Boreal Aspen Mixedwood Carbon Stocks. *Canadian Journal of Forest Research, 44,* 230-242. https://doi.org/10.1139/cjfr-2013-0165

Ribera, L., Zenteno, J., & McCarl, B. (2009). *Carbon Markets: A Potential Source of Income for Farmers and Ranchers*. Texas A&M Agrilife Extension. https://agrilifeextension.tamu.edu/asset-external/carbon-markets-a-potential-source-of-income-for-farmers-and-ranchers/

Schultz, E. B., Iles, J. C., Matney, T. G., Ezell, A. W., Meadows, J. S., Leininger, T. D. et al. (2010). Stand-Level Growth and Yield Component Models for Red Oak-Sweetgum Forests on Mid-South Minor Stream Bottoms. *Southern Journal of Applied Forestry, 34,* 161-175. https://doi.org/10.1093/sjaf/34.4.161

Schultz, E. B., Matney, T. G., & Grebner, D. L. (2013). A Tree Biomass and Carbon Estimation System. In J. M. Guldin (Ed.), *Proceedings of the 15th Biennial Southern Silvicultural Research Conference. E-Gen. Tech. Rep. SRS-GTR-175* (Vol. 175, pp. 317-324). US Department of Agriculture, Forest Service, Southern Research Station.

Sedjo, R. A., & Marland, G. (2003). Inter-Trading Permanent Emissions Credits and Rented Temporary Carbon Emissions Offsets: Some Issues and Alternatives. *Climate Policy, 3,* 435-444. https://doi.org/10.1016/s1469-3062(03)00051-2

Shaw, J. D. (2009). Using FIA Data in the Forest Vegetation Simulator. In W. McWilliams, G. Moisen, & R. Czaplewski (Eds.), *Forest Inventory and Analysis (FIA) Symposium* (Vol. 56, 16 p., pp. 1-16). US Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Shaw, J. D., & Long, J. N. (2007). A Density Management Diagram for Longleaf Pine Stands with Application to Red-Cockaded Woodpecker Habitat. *Southern Journal of Applied Forestry, 31,* 28-38. https://doi.org/10.1093/sjaf/31.1.28

Shoch, D. T., Kaster, G., Hohl, A., & Souter, R. (2009). Carbon Storage of Bottomland Hardwood Afforestation in the Lower Mississippi Valley, USA. *Wetlands, 29,* 535-542. https://doi.org/10.1672/08-110.1

Smith, H. D., Hafley, W. L., Holley, D. L., & Kellison, R. C. (1975). *Yields of Mixed Hardwood Stands Occurring Naturally on a Variety of Sites in the Southern United States*. Technical Report, School of Forest Resources, North Carolina State University.

Smith, J. E., Heath, L. S., Skog, K. E., & Birdsey, R. A. (2006). *Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States*. Gen. Tech. Rep. NE-343, U.S. Department of Agriculture Forest Service, Northeastern Research Station.

Spurlock, S. R., Munn, I. A., & Henderson, J. E. (2018). *Procedures Used to Calculate Property Taxes for Agricultural Land in Mississippi*. Mississippi State University Mississippi Agricultural and Forestry Experiment Station Information Sheet Np. 1350.

Sullivan, A. D., Matney, T. G., & Hodges, J. D. (1983). Variable Density Yield Tables for Red Oak-Sweetgum Stands. In *Proceedings of the 2nd Biennial Southern Silvicultural Research Conference* (Vol. 24, pp. 298-301). US Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.

Tanger, S., & Norman, C. (2022). *Forest Carbon Credit Programs in Mississippi. Natural Capital Exchange*. Mississippi State University Extension Publication 3738.

United States Department of Agriculture Soil Conservation Service (1961). *Land Capability classification*. U.S. Department of Agriculture Handbook 210. http://www.nrcs.usda.gov/Internet/fse_documents/nrcs142p2_052290.pdf

United States Environmental Protection Agency (2017). *Level III and IV Ecoregions of the Continental United States*. https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states

US Environmental Protection Agency (2023). *EPA Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances*. Docket ID No. EPA-HQ-OAR-2021-0317. 170 p.

van Breugel, M., Ransijn, J., Craven, D., Bongers, F., & Hall, J. S. (2011). Estimating Carbon Stock in Secondary Forests: Decisions and Uncertainties Associated with Allometric Biomass Models. *Forest Ecology and Management, 262,* 1648-1657. https://doi.org/10.1016/j.foreco.2011.07.018

Vieilledent, G., Vaudry, R., Andriamanohisoa, S. F. D., Rakotonarivo, O. S., Randrianasolo, H. Z., Razafindrabe, H. N. et al. (2012). A Universal Approach to Estimate Biomass and Carbon Stock in Tropical Forests Using Generic Allometric Models. *Ecological Applications, 22,* 572-583. https://doi.org/10.1890/11-0039.1

Walters, D. K., & Ek, A. R. (1993). Whole Stand Yield and Density Equations for Fourteen Forest Types in Minnesota. *Northern Journal of Applied Forestry, 10,* 75-85. https://doi.org/10.1093/njaf/10.2.75

Wharton, C. H., Kitchen, W. M., Pendleton, E. C., & Sipe, T. W. (1982). *Ecology of Bottomland Hardwood Swamps of the Southeast: A Community Profile*. FWS. OBS-81/37, US Department of the Interior Fish and Wildlife Service, Biological Services Program.

Wigginton, J. D., Lockaby, B. G., & Trettin, C. C. (2000). Soil Organic Matter Formation and Sequestration across a Forested Floodplain Chronosequence. *Ecological Engineering, 15,* S141-S155. https://doi.org/10.1016/s0925-8574(99)00080-4

Zianis, D., & Mencuccini, M. (2004). On Simplifying Allometric Analyses of Forest Biomass. *Forest Ecology and Management, 187,* 311-332. https://doi.org/10.1016/j.foreco.2003.07.007