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Abstract: South Carolina (SC) has a variety of different forest types, and they all have potential to sequester a certain amount of carbon. Private forest landowners control a significant portion of the overall forestland in SC, and their management efforts can maintain or improve forest carbon stocks. Currently, the second largest carbon market in the world is the California Carbon Market, which gives a monetary value to sequestered carbon. One carbon credit is equal to one metric ton of carbon and is currently worth around $15.00. Forest management plans are geared toward increasing carbon sequestration over time. This study aims to educate forest landowners about various forest management practices that contribute to increasing carbon stocks by looking at various forest types and locations in SC and their current and projected carbon stocks. Forest Inventory Analysis (FIA) data were utilized in the Forest Vegetation Simulator (FVS) to project carbon sequestration for 100 years for 130 plots. A variety of management practices were employed to see the variance in carbon sequestration. Results showed that carbon sequestration would increase for certain management practices such as thinning and prescribed fire. Clear cutting over time was harmful to sequestration. This data will be beneficial for forest landowners interested in a carbon project and those interested in seeing how different management practices affect carbon sequestration.

Keywords: carbon markets; forest management; carbon stocks; Forest Inventory Analysis

1. Introduction

Forests are an important tool for carbon storage and provide a variety of ecosystem services, including the reduction of ambient CO_2 levels [1,2]. A global carbon sink sequesters a certain amount of carbon that is a result of anthropogenic activities and can result in reduced carbon levels in the atmosphere [2]. These carbon sinks are important assets for mitigating climate change across the world. Forest type is known to have an effect on the quantity of carbon that can be sequestered [2,3]. Furthermore, when management regimes change for different forest types, these changes can have an effect on the carbon storage capabilities [2,4]. On the basis of our knowledge of how forest type and management regimes can affect carbon sequestration, these factors can play a major role for landowners who are interested in participating in the California Carbon Market or other carbon markets.

The California Carbon Market encourages landowners across the country to sell offset credits to industries in California that are required to purchase offset credits. Offset credits are project-based carbon credits, where certain forestry or other types of projects can mitigate carbon emissions [5,6]. Certain industries are required to purchase these credits to offset their emissions and adhere to carbon reduction targets [5]. One metric ton of CO_2 is equivalent to one carbon credit. Credits are currently sold for around $12–$15 per credit [7]. The use of offsets provides an opportunity for increased landscape-scale restoration [6]. Through offset sales, landowners are encouraged to reduce the chance of deforestation and maintain their forested land at least for the length of time the conservation easement is enforced. As of 2012, data indicates that 731 million forested acres in the U.S. can sequester around 10% of annual CO_2 emission in the U.S. [8]. The expansion of the California Carbon Market and other carbon regulatory frameworks is expected to provide a market incentive and increase the desire for private landowners to manage forested land in a way that sequesters carbon and preserves the forest.

The Climate Action Reserve (CAR) was created by the California Climate Action Registry (CCAR) in 2008 as a registry for carbon offset credits [5]. This organization helps landowners understand how the carbon market works, provides protocols for certifying offset credits, and aids in project verification [9]. Landowners who are interested in certifying offset credits from their forest land must enter into a 100-year conservation easement and must have a third party verify carbon sequestration every six years [9,10]. Verification of the carbon credits requires that the carbon being measured is a change or increase in carbon from a previously verified value, otherwise known as a common practice value for aboveground carbon [9,11]. While this value indicates carbon stocks in a certain region (static values), carbon sequestration represents a rate of change in carbon stocks over time. For an improved forest management project that is discussed in this paper, the landowners must start with a plot of forest land and use sustainable management to increase carbon stocks, i.e., enhancing carbon sequestration. Verification is crucial to determine as accurately as possible the actual rates of carbon sequestration and to reduce leakage [12]. Verification takes place every six years to determine if management practices or the amount of credits issued needs to change [9].

The following study outlines how various forest stands in South Carolina (SC) respond to a variety of management practices using a forest growth model to predict changes over 100 years. Carbon sequestration values over 100 years gained from the forest growth model will help forest landowners have an idea if selling offset credits on their forestland would be a profitable endeavor.

This forest analysis will (1) determine if an increase in carbon stocks is predicted over 100 years in South Carolina forests, warranting a carbon project, (2) determine the effects of location within the state and forest type on carbon sequestration, and (3) determine which management practices are the most productive in terms of carbon stocks.

2. Methods

2.1. Software and Data

This project was carried out utilizing United States Department of Agriculture (USDA) Forest Service data from the Forest Inventory Analysis (FIA) database [13,14]. This database includes a variety of forest types and survey information for most forested lands in most states. All of the analyzed plots are one acre (0.4 hectares) in size. Data for specific forest types in South Carolina were extracted, then converted into files that were readable by the Forest Vegetation Simulator (FVS) [15,16]. FVS was created by the USDA Forest Service with the intention of modeling forest dynamics on the basis of a variety of different management practices and disturbances. FVS is a semi-distance-independent forest growth model, where individual trees within a stand are primarily analyzed, and the spatial variability is statistically represented [12]. Projections from this model are most representative when using stand data. The various parameters analyzed to determine growth and yield are based upon data specific to geographic location, i.e., there are different growth equations used for different areas of the United States [17]. This model has been used since the 1970s and has extensive validation [18–21]. Furthermore, FVS is consistently used by carbon developers across the country to model carbon sequestration specifically for the California Carbon Market Compliance Protocol [14,22]. In a study by Nunery et al. (2012), FIA data were projected out for 160 years to determine carbon storage [23]. Also, a study by Russell-Roy et al. (2014) utilized FVS to predict carbon sequestration over 100 years in Vermont, USA, utilizing CAR protocols [24]. There are also many post processors that are available in the software suite. One of these includes the carbon report, which analyzes the carbon stocks every cycle, based upon the management or disturbances that are activated by the user. Carbon data are directly related to the biomass reports that are first derived from FIA data then manipulated in the model. Additionally, since FVS is a stand dynamics model, the carbon report is flexible every 5 or 10 years and is reflective of the management parameters selected [17].

2.2. Data Analysis

Four major forest types were analyzed. These include loblolly pine, longleaf pine, oak–hickory, and oak–sweetgum–cypress. FIA data showed that these were the most prolific forest types in South Carolina, and many landowners would have these forest types on their property. In total, 130 plots were chosen to model (Figure 1). Table 1 shows how many stands were analyzed for each forest type and the percent that forest type accounts for out of the total forested land in SC [9].

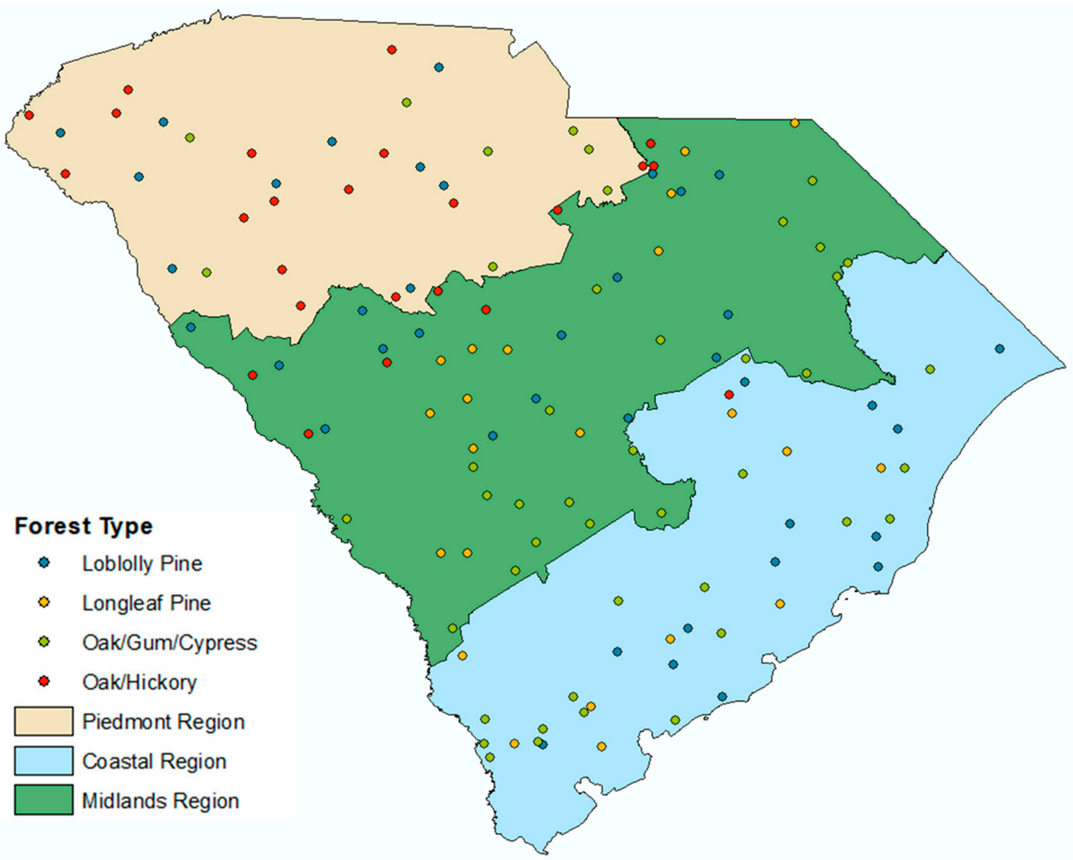

Figure 1. SC (South Carolina) Forest Inventory Analysis (FIA) plot locations identified by forest type analyzed in this study.

Table 1. Forest type, number of stands analyzed, and percentage of that forest land in South Carolina (SC).

Forest Type	Stands Analyzed	% of Forested Land
Loblolly pine	39	43.4
Longleaf pine	22	4.3
Oak–Hickory	24	22.1
Oak–Gum–Cypress	45	14.7

We selected the plots by their compatibility with the FVS model. They were also selected on the basis of age and location within the state. Ideally, at least three stands within each age bracket (as determined through natural breaks based upon available stands in ArcMap) and location within the state, i.e., Piedmont, Midlands, and Coast, were chosen for the analysis. The goal was 45 stands for each forest type (3 regions × 5 age brackets × 3 stands per age bracket and stand), but due simply to the lack of availability of the necessary amount of stands that were viable for FVS, only oak–gum–cypress had the full 45 stands. For longleaf pines, there were no stands in the Piedmont area, so data will only show stands in the midlands and coastal area. For oak–hickory, there were no stands in the Coastal area, so only data from the Piedmont and Midlands are included.

2.3. Management Practices

Key features that are important in the model include tree species, density, diameter, height, crown ratio, diameter growth, and height growth [16,25]. Variables for each FIA plot analyzed included the aspect, elevation, slope, density, and site potential [16]. All of these variables were consistent for each stand analyzed (data obtained from the FIA), and the only changes regarded the 10 management practices. The management practices indicated in Table 2 were implemented for all stands* (* Longleaf pine forest did not have any clear-cut managements (1, 2, or 4) as this is unrealistic for longleaf pine stands in SC [26]). They are referred to by their number in the results. The parameters indicated in the "Notes" section of Table 2 correspond to the input requirements of the model for each management practice. (See Appendix A for a description of the terms used in Table 2.)

The above management practices were applied to all stands equally, and projections were run from 2016 to 2116, with a five-year increment, which generated a carbon stock value (tons/acre) every 5 years and a carbon removed value (tons/acre) every 5 years. The carbon stock values are representative of aboveground and belowground live and standing dead carbon stocks (soil carbon is not included in the compliance protocol for offset credits in the California Carbon Market) [14]. The carbon removed values are representative of any merchantable wood removed from the forest in the model. Carbon values for each stand in each management practice were recorded.

2.4. Normalization

The baseline carbon value was determined from FIA data, and 2016 is the baseline year, so the data provided for the year 2016 were utilized as the baseline for all stands.

A normalized value was determined for each stand and each management practice. This value was calculated using the below equation:

$$\text{Normalized Value} = \text{CSV}/\text{BC}, \tag{1}$$

where CSV = average carbon stock value (averaged values from 20 outputs, i.e., five-year cycles were averaged for a 100-year carbon sequestration average) and BC = baseline carbon value (year 2016). The baseline carbon value was derived from the 2016 data for each FIA plot.

The results throughout the paper are reported as normalized values. Normalized values indicate the rate of sequestration over time in reference to the baseline, and this value is crucial to calculating carbon credits and subsequently compensating the landowners. While the baseline for carbon projects is often calculated using a more region-specific value, using a specific value in this case for each plot provides exact values for sequestration over time and a more accurate understanding of sequestration on each plot. Baseline and projected carbon stock values for all plots and information about all plots can be found in the excel tool created to read the data from this project. The link to the tool can be found here and also in Appendix A at the end of the paper. This link is beneficial for landowners looking to plan for participating in the carbon market, but landowners must know that these values are only representative of carbon sequestered on that exact plot from 2016 to 2116 and additional modeling on their own property would be required to comply with the California Carbon Market requirements. Values are reported in tons/acre.

Table 2. Management practices used in Forest Vegetation Simulator (FVS).

Management Identifier	Step #	Management Description	Year	# of Years after 2016	Notes	
1	1	Clear cut	2036	20	5 Legacy Trees @ 15 in min.	Smallest DBH: 5 in
	2	Artificial Regeneration	2038	22	75% survival	Species same as forest type
	3	Clear cut	2051	35	5 Legacy Trees @ 15 in min.	Smallest DBH: 5 in
	4	Artificial Regeneration	2053	37	75% survival	Species same as forest type
	5	Clear cut	2086	70	5 Legacy Trees @ 15 in min.	Smallest DBH: 5 in
	6	Artificial Regeneration	2088	72	75% survival	Species same as forest type
2	1	Thin from below	2031	15	Residual Density: 75% trees/acre	
	2	Clear cut	2036	20	5 Legacy Trees @ 15 in min.	Smallest DBH: 5 in
	3	Artificial Regeneration	2038	22	75% survival	Species same as forest type
	4	Thin from below	2046	30	RD: 50%	
	5	Clear cut	2051	35	5 Legacy Trees @ 15 in min.	Smallest DBH: 5 in
	6	Artificial Regeneration	2053	37	75% survival	Species same as forest type
	7	Clear cut	2086	70	5 Legacy Trees @ 15 in min.	Smallest DBH: 5 in
	8	Artificial Regeneration	2088	72	75% survival	Species same as forest type
3	1	Thin from below	2031	15	RD: 75% trees/acre	
	2	Thin from below	2046	30	RD: 50%	
	3	Thin from below	2076	60	RD: 50%	
4	1	Clear cut	2026	10	5 Legacy Trees @ 15 in min.	Smallest DBH: 10 in
	2	Artificial Regeneration	2028	12	75% survival	Species same as forest type
5	1	Thin from below every 15 years	Begin in 2026	10	Residual Density: 75% trees/acre	
6	1	Thin to Q-Factor (Thin every 20 years)	Begin in 2031	15	Minimum Basal Area: 120	Q-Factor: 1.4
7	1	Thin to Q-Factor-2 (Thin every 30 years)	Begin in 2031	15	Minimum Basal Area: 80	Q-Factor: 1.4
8	1	Prescribed Burn (Early Spring)	Every 7 years	Beginning in 2019	Wind Speed: 5 mph; Air Temp: 45 °F; 50% land burned; Fuel Designation: 3 = Dry	
9	1	Prescribed Burn (Early Spring)	Every 3 years	Beginning in 2019	Wind Speed: 5 mph; Air Temp: 45 °F; 50% land burned; Fuel Designation: 3 = Dry	
0	1	No Management				

2.5. Statistical Analysis

Statistical analysis was completed to determine: (1) the differences in carbon sequestration between management practices among all stands by forest type and (2) the difference in normalization means based on plot age among all stands by forest type. Statistical analysis was carried out using SPSS™ (IBM SPSS Statistics Grad Pack 25.0, Armonk, NY, USA), the ANOVA least significant difference (LSD) model for the management-based sequestration comparisons, and the non-parametric Kruskal–Wallis one-way ANOVA test for age comparisons. All values declared significant were characterized by $p < 0.05$. This statistical analysis will help landowners make more informed decisions about which of these management practices will significantly affect carbon sequestration on their land depending on forest type and age, so they can take into consideration other management actions for other goals.

3. Results and Discussion

3.1. Loblolly Pine Forest

Loblolly pine forests are extremely prevalent in SC. The majority of forest lands in SC are dominated by loblolly pine [27]. A variety of different management practices can provide increased carbon stocks over 100 years.

Among the three different regions of SC, Piedmont, Midlands, and Coast, 39 loblolly plots were studied. Three stands that were all under the age of two years did not have any carbon sequestration on the property for any management plan for the projected 100 years. All data hereafter do not include these three stands. Management Methods 3 and 5 (thin from below 1 and 2) and Management Method 0 (no management) provided an overall increase in carbon stocks over 100 years for all analyzed stands. Management Methods 8 and 9 (prescribed burns) provided an overall increase in carbon stocks for 33 and 29 stands, respectively. Management Methods 4, 6, and 7 (clear cut—3; thin to Q-factor; thin to Q-factor—2) provided an overall increase in carbon stocks for 27, 26, and 24 stands, respectively.

For 28 loblolly pine plots, no management (Management Method 0) generated the largest average carbon stock over 100 years. Seven stands generated the most carbon stocks using Management Method 5 (thin from below). One stand generated the most carbon using Management Method 4 (clear cut—3). If no management was not considered for maximum average carbon stocks, 34 stands would have generated the maximum average carbon stock using Management Method 5 (thin from below—2). The minimum value of carbon stocks was generated most often using Management 1 and 2 (clear cut 1 and 2).

The difference in rates of carbon sequestration can be attributed to the management performed on the property, specifically, the carbon that is removed due to thinning, burning, or uneven aged thinning/large tree removal [28]. The number of stands in this study with increases in carbon sequestration is significant because of the various parameters of each plot; the more the plots that have similar carbon sequestration rates per management practice, the higher the applicability of the management practice at different locations.

Management Method 0 (no management) had the highest normalization value, indicating that the greatest amount of carbon would be sequestered with no management in these forest stands. Management 1 and 2 (clear cut) had the lowest normalization values, which were lower than 1, indicating that the values of carbon would not be greater than the baseline values. For most of the management practices, the normalization values were significantly higher in the Piedmont region and brought the average up for the entire state. This may show ($p < 0.05$) that all the management practices (except for 1 and 2) would increase carbon stocks solely depending on the location (Table 3).

Management Method 5 maintained carbon stock values closest to those of no management. This may be a more effective management regime than no management to reduce the potential for fire and pest issues. Other management practices such as Management 8 (prescribed burn—1) may provide the desired carbon stocks while reducing the threat of uncontrolled fire or disease. Furthermore, Management 6 and 7 provided smaller carbon stocks, but may provide another source of income due to the uneven-aged cutting. These benefits and tradeoffs would need to be determined by the specific landowner.

Upon analysis of the differences in carbon sequestration for all management practices based upon age, it was determined that the younger plots had a much higher sequestration rate ($p < 0.05$) than the rest of the stands (Table 4). This is likely due to the fast-growing rate of loblolly pines in the first stage of life. Additionally, loblolly pines are one the most commonly harvested tree in SC. This increases the unnatural disturbances that the land receives at a rate of every 25–35 years depending on management. These disturbances can have a significant effect on the carbon sequestration due to harvest and subsequent stand regeneration [28] ("*n*" in the chart is the number of plots analyzed in that age range.)

Table 3. Normalization values (avg. carbon stock value/baseline carbon value) for loblolly pine plots.

Management Regime	Coast	Midlands	Piedmont	Overall Average
1 [a]	0.8	0.8	0.9	0.9 ± 0.1
2 [a]	0.8	0.9	1.0	0.9 ± 0.1
3 [b]	2.0	2.0	3.0	2.3 ± 0.6
4 [c]	1.5	1.5	2.3	1.8 ± 0.5
5 [b]	2.1	2.1	3.2	2.5 ± 0.6
6 [c]	1.3	1.4	2.3	1.7 ± 0.6
7 [c]	1.2	1.3	2.0	1.5 ± 0.4
8 [c]	1.6	1.7	2.4	1.9 ± 0.4
9 [c]	1.3	1.4	1.9	1.5 ± 0.3
0 [b]	2.1	2.2	3.4	2.6 ± 0.7

[a] Significantly different between all regimes except for 1 or 2, [b] significantly different between all regimes except for 3, 5, or 0, [c] significantly different between all regimes except for 4, 6, 7, 8, or 9.

Table 4. Normalization (avg. carbon stock value/baseline carbon value) mean for all management practices separated by stand age for loblolly pine plots.

Age	Mean ± SD	*n*
1–11	2.63 ± 1.51 [a]	5
12–24	1.79 ± 1.08	9
25–36	1.52 ± 0.70	10
37–59	1.71 ± 0.90	9
60–88	1.02 ± 0.35	3

[a] Normalization values are significantly different ($p < 0.05$) from those of the rest of the samples.

3.2. Longleaf Pine Forest

Longleaf pine forests are decreasing in South Carolina, and restoration of the longleaf pine forest is paramount. Longleaf pine forests require more intensive management, specifically, artificial regeneration and often times prescribed burns. For these reasons, clear cutting is not often a viable management technique for longleaf pine forests in SC; thus, Management practices 1, 2, and 4 were not modeled.

Most management practices helped increase carbon sequestration. One stand at age 2 did not have any sequestration or foliage and will not be included hereafter. Management Method 0 (no management) provided the most carbon sequestration for 20 out of the 21 analyzed stands (Table 5).

Table 5. Normalization values (avg. carbon stock value/baseline carbon value) for longleaf pine plots.

Management Regime	Coast	Midlands	Overall Average
3 [a]	2.1	1.8	2.0 ± 0.2
5 [a]	2.2	1.8	2.0 ± 0.3
6	2.3	1.6	2.0 ± 0.5
7 [b]	1.9	1.4	1.7 ± 0.4
8 [b]	1.8	1.6	1.7 ± 0.1
9 [c]	1.3	1.2	1.3 ± 0.1
0 [d]	3.0	2.2	2.6 ± 0.6

[a] Significantly different between regime 9, [b] significantly differently between regime 0, [c] significantly different between all regimes except for 4, 6, 7, 8, or 9, [d] significantly different between regimes 7, 8 and 9.

If Management Method 0 is not included, Management Methods 5 (thin from below every 15 years), 6 (uneven-aged thin every 20 years), and 8 (prescribed burn every 7 years) were the second more productive management practices. Management Method 5 had the highest carbon sequestration averages for 13 stands. Management Method 6 had the highest carbon sequestration average for four stands. Management Method 8 had the highest carbon sequestration average for three stands.

Management Method 9 (prescribed burn every 3 years) seemed to be the most detrimental to carbon sequestration, as only 9 stands had positive carbon sequestration averages after 100 years (above the baseline) with this management, and it had the smallest carbon sequestration value among all management practices for 14 stands. Management Method 7 (uneven-aged thinning every 30 years) had 7 stands where the average carbon sequestration after 100 years went above the baseline. This management practice had the smallest carbon normalization value among all management practices for 7 stands. While prescribed burning is extremely important for the regeneration of the species and the management of the longleaf pine forest, it may not be the best choice for carbon sequestration. Additionally, multiple types of management in a longleaf pine forest may be necessary to obtain maximum sequestration.

Management Method 0 (no management) had the highest normalization value, indicating that the greatest amount of carbon would be sequestered with no management to these forest stands. Management 9 (prescribed burn every 3 years) had the lowest carbon sequestration for all stands, followed by Management 7. In terms of location, the average values in the state did vary slightly, with the coastal plots in the case being more productive in all categories of management.

The trends in the average carbon stocks over 100 years did show statistically significant correlations ($p < 0.05$) between stand ages, and the average normalization values for increases in carbon stocks compared to the baseline across all management practices did show a slight downward trend when comparing stand age (Table 6).

Table 6. Normalization (avg. carbon stock value/baseline carbon value) mean based on stand age for longleaf pine plots.

Age	Mean ± SD	*n*
2–11	2.32 ± 2.16 [a]	4
12–26	2.25 ± 0.88 [a]	7
27–60	1.42 ± 0.56	3
61–76	1.15 ± 0.38	3
77–90	1.43 ± 0.49	5

[a] Normalization values are significantly different ($p < 0.05$) from the those of the rest of the samples.

3.3. Oak–Hickory Forest

Oak–hickory forest is very prominent in the Piedmont (northwest) region of SC. These forest lands are the dominant forest type in western SC and would potentially be very important for carbon sequestration and contributing to the California Carbon Market. Historically, Oak–hickory forests are not a native forest type but they have become prominent as a result of fire suppression in the region over many years [29]. This has increased the carbon sequestration and storage of the Piedmont region, as native prairie may not have stored as much carbon [30]. Furthermore, many of the stands are older than 66 years. This may affect their ability to increase carbon stocks, as there are already significant carbon stocks in existence.

The Oak–hickory forests were managed the same as the pine forests, and many of the results were relatively the same. Management 5 (thin from below—2), Management 0 (no management), and Management 3 (thin from below) were the most effective management practices for the oak–hickory forest. Management 0 and Management 5 both had 11 stands that had the highest average carbon stocks. Management 3 had two stands that had the highest average carbon stocks. Management 5 continued to be the most effective as 10 additional stands for Management 5 had the highest carbon stocks, excluding Management 0. It was also notable that Management 3 (thin from below), Management 8 (prescribed burn), and Management 9 (prescribed burn 2) all had positive average carbon stocks after 100 years (Table 7).

Table 7. Normalization values (avg. carbon stock value/baseline carbon value) for oak–hickory plots.

Management Regime	Midlands	Piedmont	Overall Average
1 [a]	0.8	0.9	0.9 ± 0.1
2 [a]	0.7	0.9	0.8 ± 0.1
3 [a]	1.8	2	1.9 ± 0.1
4 [a]	1.2	1.5	1.4 ± 0.2
5 [a]	1.8	2	1.9 ± 0.1
6 [a]	1.3	1.4	1.4 ± 0.1
7 [a]	1.1	1.3	1.2 ± 0.1
8 [a]	1.5	1.7	1.6 ± 0.1
9 [a]	1.4	1.5	1.5 ± 0.1
0 [a]	1.8	2.1	2.0 ± 0.2

[a] Significantly different between all regimes except for 1 or 2, [b] significantly different between all regimes except for 3, 5, or 0, [c] significantly different between all regimes except for 4, 6, 7, 8, or 9, [d] significantly different between 5, 8, and 0, [e] significantly different between all regimes except 4 and 6, [f] significantly different between all regimes except 9.

It was very clear that clear cutting, even with regeneration, was very ineffective for carbon management. We found that 22 out of the 24 stands had their lowest average carbon stocks over 100 years with Management 2 (clear cut—2). One stand had its lowest average carbon stock with Management 7 (thin to Q-factor—1), and the last stand had its lowest average carbon stock with Management 1 (clear cut). Management 1 was also highly ineffective for carbon management. Management 6 and 7 (thin to Q-factor 1 and 2) did increase carbon stock averages but not at a rate that would provide significant income for the carbon market.

In terms of overall averages, Management Method 0 (no management) had the highest normalization value, indicating that the greatest amount of carbon would be sequestered with no management to these forest stands. Management 1 and 2 (clear cut 1 and 2) has the lowest carbon sequestration for all stands, followed by Management 4 and 9. Management 3 and Management 5 (thin from below and thin from below—2, respectively) were very close to Management 0. The average normalization values for the different locations were relatively close, but it is clear that the Piedmont plots had a higher average normalization value in all management categories than the Midland plots. For the Midland plots, Management 0 and 5 had the same average normalization values, whereas for the Piedmont plots, Management 0 had a slightly higher average normalization value than Management 5. These management practices are considerably different, yet they yield almost the same results.

In terms of maximization of carbon sequestration, it is known that microbial respiration has higher rates in younger stands; thus, older stands will not be as productive at sequestering carbon [31]. These factors could potentially encourage some inclusion of thinning and uneven-aged tree removal that would increase carbon sequestration. These decisions would be made at the stand/parcel level by the landowner.

The trends in the average carbon stocks over 100 years did not show statistically significant correlations between stand age, but the average normalization values for increases in carbon stocks compared to the baseline across all management practices did show a dip for middle-aged trees (age 35–65) when comparing stand age (Table 8). Furthermore, many of the stands are older than 66 years. This may affect their ability to increase carbon stocks, as older stands often sequester less carbon than younger stands [32].

Table 8. Normalization (avg. carbon stock value/baseline carbon value) mean based on stand age for oak–hickory plots.

Age	Mean ± SD	*n*
0–34	1.48 ± 0.45	5
35–57	1.26 ± 0.48	7
58–65	1.43 ± 0.48	3
66–77	1.68 ± 0.54	5
78–91	1.49 ± 0.73	5

3.4. Oak–Gum–Cypress Forest Data Analysis

Oak–gum–cypress forests were important to analyze in South Carolina because of their prominence in many lowland areas. This may mean that these areas are already providing important ecosystem services, and it is important to compensate these services and discourage the conversion of these lands that would ultimately reduce carbon sequestration.

There were a significant number of plots available to analyze this forest type, and we were able to obtain 45 plots. Unfortunately, all age groups and locations were not equally represented as there were not enough young plots or plots in the Piedmont region. The majority of the plots are primarily in the middle of the state but there are a few in the north, and many in the southern regions of the state. The plots in the southern regions are mostly older plots, ranging from 65 to 90 years. One plot was removed from the analysis due to the lack of vegetation and subsequent carbon sequestration.

The structure of the Oak–gum–cypress forest does not vary significantly from that of the oak–hickory forest, but the management practices that would be productive for carbon management are more variable for this forest type. This may be due to beneficial climate conditions that occur in these ecosystems, such as high amounts of moisture and nutrients. Additionally, many of these stands are well stocked, contributing to large carbon stocks [33]. We found that 24 stands had the highest average carbon stocks after 100 years for Management 0 (no management), 13 stands had the highest average carbon stocks for Management 5 (thin from below—2), 4 stands had two management practices with identical carbon sequestration, 2 stands had identical carbon sequestration for Management 5 and Management 0, and 2 stands had identical carbon sequestration for Management 4 and Management 0. If Management 0 was not considered in the analysis, 20 more stands would have Management 5 as the highest average carbon stocks. These stocks had often only 1–2 tons/acre (2.2–4.4 tons/hectare) of carbon less than Management 0 (Table 9).

Table 9. Normalization values (avg. carbon stock value/baseline carbon value) for oak–gum–cypress plots.

Management Regime	Coast	Midlands	Piedmont	Overall Average
1 [a]	1.3	1.1	0.7	1.0 ± 0.3
2 [a]	1.2	1.1	0.7	1.0 ± 0.3
3 [b]	2.7	2.6	1.6	2.3 ± 0.6
4 [c]	2.4	2.3	1.1	1.9 ± 0.7
5 [b]	2.8	2.7	1.6	2.4 ± 0.7
6 [d]	2.1	2.0	1.0	1.7 ± 0.6
7 [e]	1.9	1.7	0.9	1.5 ± 0.5
8 [e]	1.8	1.8	1.3	1.6 ± 0.3
9 [e]	1.3	1.2	1.0	1.2 ± 0.2
0 [b]	2.9	2.8	1.6	2.4 ± 0.7

[a] Significantly different between 3, 4, 5, 6 and 0, [b] significantly different between 1, 2, 7, 8, and 9, [c] significantly different between 1, 2, and 9, [d] significantly different between 1, 2, 5, and 0, [e] significantly different between 3, 5, and 0.

Management 1 and 2 (clear cut 1 and 2) were primarily the management practices with the lowest average carbon stocks after 100 years, as expected [34]. This accounted for 31 of the 44 analyzed stands. Notably, Management 9 (prescribed burn—2) had 10 stands that had the lowest average carbon stocks. It was definitely clear that the youngest stands were most affected by prescribed fire, and this resulted in the lowest carbon stocks. This management practice was highly variable between stands. Also, Management 4 had two stands with the lowest average carbon stocks, and Management 5 had one stand.

Management 0 (no management) had the highest normalization value, indicating that the greatest carbon would be sequestered with no management to these forest stands. This is consistent with the results of a study by Ruddell et al. [35]. Management 1 and 2 (clear cut 1 and 2) had the lowest carbon sequestration for all stands, followed by Management 9. Management 3 and Management 5 (thin from below and thin from below—2, respectively) had carbon normalization values very close to those of Management 0. For most of the management practices, the normalization values were significantly higher in the Coastal and Midlands regions, and these areas helped bring up the average, whereas the Piedmont region was not nearly as productive. These values were among the highest for a forest types, except for the Piedmont region.

While no management provided the highest carbon sequestration values for almost all stands, this may not be the best choice, depending on the land and landowner [11,36]. Consistent thinning and some prescribed burn proved to be effective for some stands, and these practices may help reduce brush that could potentially cause unwanted fires, while thinning can help reduce disease that could decimate the stand. These decisions would be made at the stand level by the landowner.

The trends in the average carbon stocks over 100 years did not show statistically significant correlations to stand age or forest type, but the average normalization values for increases in carbon stocks compared to the baseline across all management practices did show a consistent decrease, especially for the very young stands (Table 10).

Table 10. Normalization (avg. carbon stock value/baseline carbon value) mean based on stand age for oak–gum–cypress plots.

Age	Mean ± SD	*n*
0–13	4.45 ± 2.71 [a]	8
14–31	1.51 ± 0.51	9
32–43	1.40 ± 0.51	9
44–66	1.14 ± 0.44	9
67–90	1.12 ± 0.41	9

[a] Normalization values are significantly different ($p < 0.05$) from those of the rest of the samples.

3.5. Assumptions and Limitations of the Model

The FVS model is a powerful tool but may not always accurately represent what would occur in many forest stands. Each management practice does not take into account disease or unintended fire. Furthermore, it does not take into consideration the need for roads and other human-made things to take up space in the forest, thus reducing carbon stocks. The age of the stands was also a limiting factor, as very young stands (< 3 years) would have limited data inputs compared to older stands. Three loblolly stands were removed from the analysis due to a lack of inputs. While the limitations of the FVS are known in this study, the use of the FVS model is important to replicate how landowners and carbon managers project carbon sequestration on their land. It is also worth noting that the results of this study report only the carbon stocks in forest trees and those in not removed, merchantable wood. Removed, merchantable wood could result in carbon sequestration offsite, depending on the use of those wood products. Additional research and inputs in the model are needed to take into consideration climate change-related disturbances [37].

4. Conclusions

The data provided in this document cover a range of forest types and forest plots in South Carolina. In total, 130 plots were analyzed and provided a vast amount of data regarding how different management practices affect the carbon sequestration of each stand. Overall, it was determined that for most of the plots, no management at all would increase carbon stocks the most. Next, Management 5 (thin from below every 15 years) was the second most productive management practice and could potentially provide additional income through the merchantable wood harvested. Management 3 (thin from below three times) was the third most productive management practice for all stands and may be easier on landowners, as it only requires thinning three times throughout the 100-year cycle. Overall, many of the stands increased carbon stocks over the 100 years and did not decrease carbon stocks unless clear cutting was reoccurring. This shows that there is significant potential for SC forests to sequester carbon at a rate that would be viable to sell as offset credits in the California Carbon Market. Conversely, the stands that were recently planted and very young did not show positive effects for carbon sequestration over 100 years. This may be due to the limited data available for the model that are not completely reflective of what would actually occur with that specific management initiative.

Reforestation projects and expansion of current forests can have a significant impact on the accumulation of atmospheric carbon, often sequestering more carbon than natural forests [4,38]. Additionally, due to climate change and the rapid increase of CO_2 in the atmosphere, forest disturbances may heighten the potential for increased fires, pests, and drought [37,39]. These types of disturbances may invalidate the FVS model over the course of the projected 100 years. The Forest Project Protocol created to manage carbon credits under the compliance system does consider the potential for increased severity of disturbances [9,22]. A buffer pool is required for each project in case of loss of trees due to an unexpected disturbance, and additional modeling is required over time to reevaluate carbon stocks and the current rates of sequestration [22]. Due to the potential for increased tree mortality, it is possible that buffer pools will need to be increased and requirements for carbon sequestration increased if current modeling requirements (as utilized in this study) are continued [40]. The effects of climate change on long-term modeling are still poorly understood, and additional research is needed [37].

The southeastern region is the largest carbon sink in the U.S. [41]. Climate change mitigation is crucial, and the California Carbon Market could provide a means for the southeast and other regions of the U.S. to increase their capacity to be a carbon sink. Additionally, as more forest land is conserved for the carbon market or otherwise, the impact of disturbances such as disease decreases [41]. Land use also affects climate change significantly, as many natural forests have been converted to loblolly pine stands in the South, as does an increase in urbanization. It has been predicted that if agriculture prices can remain stable, forest lands can increase, and urbanization can be reduced [42]. This highlights the crucial nature of involving all landowners in the carbon sequestration process, whether that be avoided conversion on agriculture land or improved forest management on timber and non-industrial private forest lands.

Due to the availability of FIA data for most of the United States and the open access features of FVS, this project is repeatable for other states. Additionally, depending on the parameters of each plot and the management practices employed, this data could be used in other locations that are similar to plot locations in SC. Forest management is a crucial step to sequestering atmospheric carbon.

The Microsoft Excel tool created from this research also provides an easy-to-use database for landowners interested in how certain forest attributes and location affect carbon sequestration. This information can provide carbon stocks projection at 5-year intervals and 100-year averages for all management practices and stands (1234 different variations on 130 plots). While this information can be helpful in determining the differences in carbon sequestration between various plots and forest types, the actual values and additionality for carbon sequestration will not be representative of values required for the California Carbon Market due to the type of analysis done in this study. If landowners are interested in entering the carbon market, they may use the tool to determine a management practice utilized in the tool, then their own modeling must be done utilizing parameters from their own forest. This document can be found in the Appendix A.

Future research is needed to determine how income, transaction costs, and profit will relate to these different management practices and if the most productive practices determined in this study would remain the same.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Keywords for Table 2

Thin from Below: Removal of small trees based on basal area or residual density
Residual density: A measure of how many trees will be left after thinning
Thin to Q-factor: The removal of some mature, merchantable trees, retains legacy trees
Q-factor: The ratio of trees in a diameter class to the number of trees in the next diameter class
Legacy Trees: Trees that are left on the property following a harvest
DBH: Diameter (of tree) at breast height
Basal Area: A measure to describe the density of trees in a certain area
#—Number

The Microsoft Excel document created to read the data from this project can be found and downloaded online at https://bit.ly/2HlkHUa.

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