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From Farms to Forests: Landscape Carbon Balance after 50 Years of Afforestation, Harvesting, and Prescribed Fire

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Abstract: Establishing reliable carbon baselines for landowners desiring to sustain carbon sequestration and identify opportunities to mitigate land management impacts on carbon balance is important; however, national and regional assessments are not designed to support individual landowners. Such baselines become increasingly valuable when landowners convert land use, change management, or when disturbance occurs. We used forest inventories to quantify carbon stocks, estimate annual carbon fluxes, and determine net biome production (NBP) over a 50-year period coinciding with a massive afforestation effort across ~80,000 ha of land in the South Carolina Coastal Plain. Forested land increased from 48,714 ha to 73,824 ha between 1951 and 2001. Total forest biomass increased from 1.73–3.03 Gg to 17.8–18.3 Gg, corresponding to biomass density increases from 35.6–62.2 Mg ha^{-1} to 231.4–240.0 Mg ha^{-1}. Harvesting removed 1340.3 Gg C between 1955 and 2001, but annual removals were variable. Fire consumed 527.1 Gg C between 1952 and 2001. Carbon exported by streams was <0.5% of total export. Carbon from roots and other harvested material that remained in-use or in landfills comprised 49.3% of total harvested carbon. Mineral soil carbon accounted for 41.6 to 50% of 2001 carbon stocks when considering depths of 1.0 or 1.5 m, respectively, and was disproportionately concentrated in wetlands. Moreover, we identified a soil carbon deficit of 19–20 Mg C ha^{-1}, suggesting opportunities for future soil carbon sequestration in post-agricultural soils. Our results provide a robust baseline for this site that can be used to understand how land conversion, forest management, and disturbance impacts carbon balance of this landscape and highlight the value of these baseline data for other sites. Our work also identifies the need to manage forests for multiple purposes, especially promotion of soil carbon accumulation in low-density pine savannas that are managed for red-cockaded woodpeckers and therefore demand low aboveground carbon stocks.

Keywords: agrarian change; biomass; carbon cycle; carbon sequestration; inventory; reforestation; soil carbon

1. Introduction

The southeastern USA is an important region for assessing temporal dynamics of carbon (C) stocks in response to both management and natural processes. This region contains about 10% of national C stocks and produces over 60% of wood-based products in the USA [1,2]. Net C sequestration in southeastern USA exceeds most other regions but is expected to decline in the next few decades, primarily due to forest aging and conversions to urban and non-agrarian development [3,4]. Overall, forest cover has increased dramatically since the 1950s because the environmental conditions are poor for large-scale production of many crops with the exception of hay and pasture, particularly in the upper coastal plain sub-region. Forest cover of this region is comprised of various pine and hardwood species, with a wide range of forest management overlain on past land conversions. Currently, forested land in this region consists of: 68% managed non-industrial forest; 17% industrial forest; 12% public lands; and only about 3% in parks or reserves, not including de-facto reserves such as stream-side buffers and conservation easements [5]. These diverse forest and land use patterns affect both above- and belowground C. Forest management currently focuses on the highest value products and revenue (e.g., solid lumber and utility poles), followed by pulpwood for paper. Bioenergy chips and pellets are currently only produced from sawmill waste and other residues [6]. However, new forest management initiatives in the region could reduce the C sequestration, such as efforts to restore native pine savanna with fire, which have much longer rotations and lower tree densities [7]. Short rotation woody crops are also being evaluated for bioenergy and pulp production [8–10]. These initiatives are only constrained by market conditions, and air and water quality regulations. When these are combined with existing practices, vegetation succession, and mortality will likely lead to dramatic changes in C stocks and fluxes. Therefore, establishing a reliable C baseline for individual landowners (e.g., federal and state governments, timber companies, NGOs, and private landowners) who desire to sustain the C sequestration, and to identify opportunities to mitigate land management impacts is important, especially under recent initiatives and potential future policy mandates [11].

National or regional C assessments, although spatially explicit, are not designed to support individual landowners as they generally lack the spatial resolution and data accessibility required [12]. If baseline conditions can be established, modeling the subsequent impact of management alternatives on C stocks and fluxes can provide some estimate of change, but baseline conditions and model parameterization must be site specific and consider effects on all C cycle components [13,14]. However, insufficient knowledge of the natural variation in C cycle processes, catastrophic mortality, and C responses to silvicultural treatments currently exists to reliably model C dynamics over an entire landscape [15,16]. These challenges suggest that some effort to measure C through inventory and monitoring is required to characterize C cycle components that are either spatially variable or sufficiently dynamic and could therefore violate assumptions in regional inventory or modeling tools. For individual forest landscapes, monitoring can itself be a major challenge because of costs, and most inventories focus on efficient estimates of commercial products. Although inventory methods are evolving and new approaches may help reduce costs and provide additional information on C cycle components at a smaller spatial scale [17], these new approaches are not currently applicable to individual landowners. Understanding the challenges and opportunities associated with establishing a reliable C baseline for landowners will have significant implications for management policies and practices, and for detecting change in C stocks in the future [18].

Carbon baselines become critical if public policies, taxes, or markets cause landowners to convert current land use, change management strategy, or if a major disturbance occurs because these activities can have substantial impacts, either positive or negative, on the C balance. Agrarian change, the conversion of a forest to agriculture production, results in a large and immediate reduction in aboveground carbon stocks, usually accompanied by slower, but also large reductions in the belowground C. Disturbances, such as windthrow, wildfire, and drought, can have similarly negative impacts on the C balance [19,20]. Forest management can have large and immediate impacts or more delayed and subtle impacts on the C balance. For example, clearfelling, thinning, or conversion of high-density plantation to low-density savanna all impose immediate removals of aboveground C stocks; however, these management activities should then be followed by increases in both the above- and belowground C. Afforestation of agrarian landscapes rapidly increases aboveground biomass that continues to increase through time until thinning or harvest [21]. Indeed, the pace and pattern of the aboveground C increases have been estimated for many forest types in the USA [22]. However, much less is understood about belowground responses and soil C accumulation in response to afforestation efforts [23,24], although a recent meta-analysis suggests that increases in soil C following afforestation of agrarian sites may not be apparent for 30 years or more [21]. Without a robust C baseline, C dynamics in response to land conversion, land management, and disturbance cannot be adequately quantified.

The Savannah River Site (SRS) in South Carolina, USA, is an 80,000 hectare (ha) National Environmental Research Park owned and operated by the United States Department of Energy (Figure 1). Although the primary missions are national security and defense, environmental and natural resource management responsibilities have facilitated development of extensive databases that allow detailed examination of C stocks, fluxes, and net biome production (NBP) associated with land use and forest management that would not be available on most ownerships [25]. It is sufficiently large enough to represent a heterogeneous array of non-agrarian ecosystems embedded within the regional upper coastal plain biome. Moreover, the SRS landscape has undergone substantial land use conversion, beginning with agrarian development after European settlement centuries ago, then land abandonment after the US Civil War in 1865 due to tax policies, which was followed by increases in farming at the turn of the century when cotton and other crop prices increased prior to the global economic depression in the 1930s [26]. An afforestation effort, of what was primarily an agrarian landscape, began in 1951 when the US Government condemned and purchased the land to create a secure nuclear materials facility. Our objectives are to (1) quantify C stocks in vegetation in 1951 and 2001; (2) estimate annual C fluxes and life cycle residues over the period; and (3) determine (NBP). The recommended baseline for carbon accounting by the Intergovernmental Panel on Climate Change is 2000 [27]. We consider results in terms of active forest management effects on the net C sequestration, the applicability of national and regional C information, and our ability to detect change in the C cycle components in the future. In addition, we discuss the changes in forest condition since 2001 and the potential impacts of future land use and forest aging on C cycle balances.

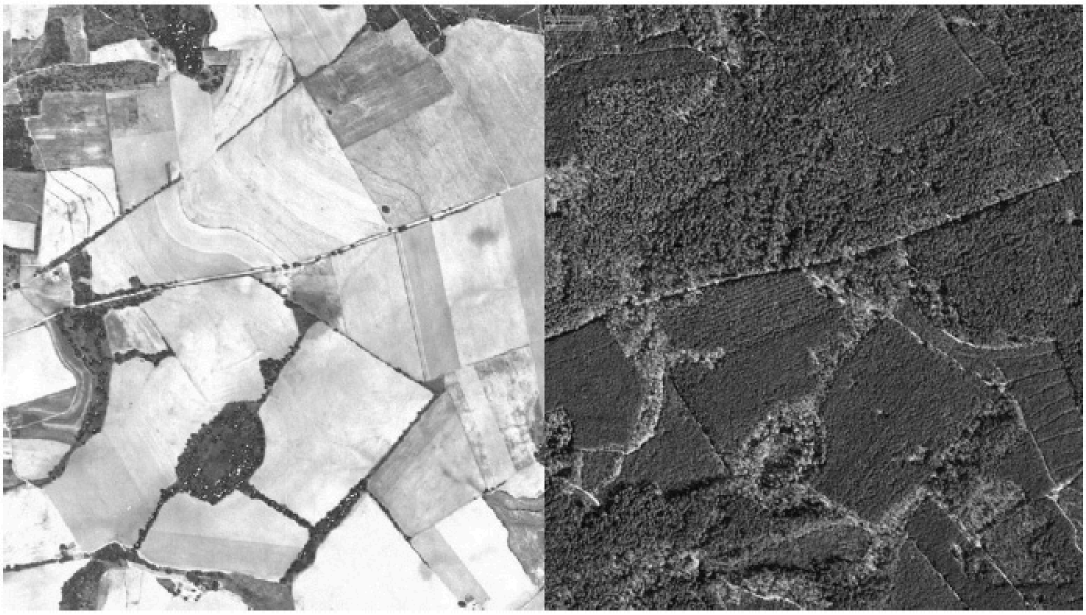

Figure 1. An aerial image from 1951 showing an area that is currently within the 80,000 ha Savannah River Site but was primarily under agriculture at that time (**left**), and that same area in 2001, illustrating the profound impact of afforestation across the landscape (**right**).

2. Methods

2.1. Study Area

The SRS is located on the Upper Coastal Plain and Sandhills physiographic provinces in South Carolina, USA. The elevational range is small (~100 m) and the average rainfall is about 1200 mm. About 85% of the land area has well drained upland soils and 15% has hydric or flooded soils as a consequence of complex topographic and hydrological characteristics. Upland soils are sandy and well-drained, whereas wetland soils are generally poorly drained loams. The forest site productivity index for southern pines averages about 27 m in fifty years (dominant tree heights) but varies from a low of 18 m on xeric deep sands to a high of 36 m on mesic soils high in organic matter [28]. When SRS was established in 1951 by the US Government, land use consisted of agricultural farms, naturally regenerated pine forest on previously abandoned farms, a few pine plantations, and substantial amounts of cutover forest land (Table 1 and Figure 1). Agrarian tillage impacted >70% of the landscape since European settlement [26]. Several major periods of farm abandonment and conversion to forest occurred in the decades following the US Civil War and through the turn of the 19th century [26]. When SRS was established, reforestation occurred on approximately 33,000 ha of farm fields and thousands of hectares of cutover forest [25]. Long-term removals of wood, dating from the middle of the 19th century, resulted from the manufacturing of lumber, box crates, and pulp. However, much of the cutover forest resulted from harvests immediately prior to the SRS establishment in 1951 because timber was not included in the land purchase price by the US government, thus landowners liquidated their resources. Agricultural fields and cutover forests were subsequently planted with loblolly (*P. taeda* L.), longleaf (*P. palustris* Mill.) and slash pine (*P. elliottii* Engelm. var. elliottii) in the decades following formation of SRS [25].

Table 1. Land use and land cover conditions in 1951 and 2001 based on the inventories during those periods. Woodland and forest cover groups are described in the text.

Land Use/Cover 1951	Area (ha)	Land Use/Cover 2001 [1]	Area (ha)
Total Agricultural	32,465.5	Total Developed	6349.6
Crops	30,984.2	Industrial	2471.6
Pasture	1295.2	Lakes & Ponds	1430.0
Ponds	186.1	Rights of Way (open)	2448.0
Total Woodland	48,714.5	Total Forest Cover	73,824.4
Pine	22,584.2	Pine Plantation	50,025.1
Pine Plantation	1738.8	Pine-Hardwood	2197.5
Hardwood	9804.1	Hardwood-Pine	2167.1
Swamp	10,905.8	Hardwood	16,732.5
No Growing Stock [2]	3681.4	Cypress-Tupelo	2702.2
Total	81,180.0		80,174.0

[1] 1006 ha of forest land was transferred to Barnwell county in the 1970s; [2] Primarily pine and pine plantation lands.

SRS currently contains approximately 74,000 ha of forests divided into about 6000 mapped stands (Table 1 and Figure 1). These stands range from cypress-tupelo swamp, hardwoods, mixed-hardwoods, to pine plantations. Hardwood and mixed-hardwoods are diverse with over 100 tree species that are predominately of natural origin and occur as isolated patches on xeric and mesic soils in the uplands and large continuous forest on poorly drained bottomlands. Forest rotations range from 50 to 120 years, depending upon the stand type and management objectives [28]. Thinning occurs on about 2000 ha and clearfelling occurs on about 300 ha. The mean volume harvested from 1991 to 2001 was about 140,000 m^3 $year^{-1}$ [24]. None of the cypress-tupelo swamp and very little hardwood are currently harvested. No fertilization or planting of genetically improved stock occurs, except for relatively small-scale research purposes (e.g., [29–32]). Wildfire frequency at SRS is low compared to other federal lands in the southeastern USA. Prescribed fire is currently targeted to treat 8000 ha $year^{-1}$ to 10,000 ha $year^{-1}$ in upland areas to restore the pine savanna habitat and reduce hazardous-fuels. Forest inventories have been conducted every decade since 1951 and the total gross merchantable volume for these periods has been reported [25]; however, only 1951 and 2001 provide sufficient data for detailed C assessments. Detailed descriptions of inventory methods can be found in the supplementary methods (SM).

2.2. Estimates of Forest & Non-Forest Biomass

We applied two methods (hereafter, Method A & B) to the 1951 and 2001 inventory data to determine the aboveground tree biomass, C, and NBP. More detailed descriptions of forest and non-forest biomass estimation methods can be found in the supplementary methods (SM). Figure 2 provides a conceptual model of our approach for calculating biomass and carbon stored in vegetation and residues. Briefly, Method A [33] uses simple expansion factors, or multipliers, developed for each region in the US for softwoods and hardwoods separately to convert the commercial growing stock volume per unit area (m^3 ha^{-1}) to the total aboveground (alive and dead) tree biomass density (Mg ha^{-1}). The expansion factor is the simplest approach to convert commercial growing stock to the total aboveground C density (Mg C ha^{-1}) that includes non-commercial biomass, assuming C is 50% of dry biomass. Method A assumes a linear relationship between the two variables and one value for conversion of the tree volume to the biomass density dependent only on broad forest composition designation, such as conifer or hardwood. It was designed for large spatial scale aggregate estimates and the expansion factors are derived from the national inventory plot data Forest Inventory and Analysis (FIA) data, within various regions. Method B [34] was designed to refine and improve on Method A. It also uses the FIA plot data from each region. However, rather than a single conversion, the authors developed non-linear regression equations between the commercial growing stock volume density (m^3 ha^{-1}) on each plot and the total aboveground (alive and dead) tree biomass density (Mg ha^{-1}) for broad forest types within each region. It eliminated the assumption of a single conversion factor. The authors employed a national meta-analysis by Jenkins et al. [35] that created the volume to biomass allometric equation for species groups and genera. Method B is believed to be a more accurate approach for conversion of the individual trees commercial volume to the total aboveground biomass on each plot. Chojnacky et al. [36] subsequently updated and improved the individual tree volume to biomass equations. Since we had individual tree measurements for 2001, we could apply these updated equations directly to provide an alternative check on the live aboveground tree biomass and C stocks in 2001 using Methods A and B. We developed a separate procedure to estimate the mass of standing dead trees from site-specific studies (see SM). To estimate the biomass in the abandoned crop and pasture lands in 1951, we used the comprehensive studies of abandoned agricultural field succession and development done at the SRS in the early 1950s [37].

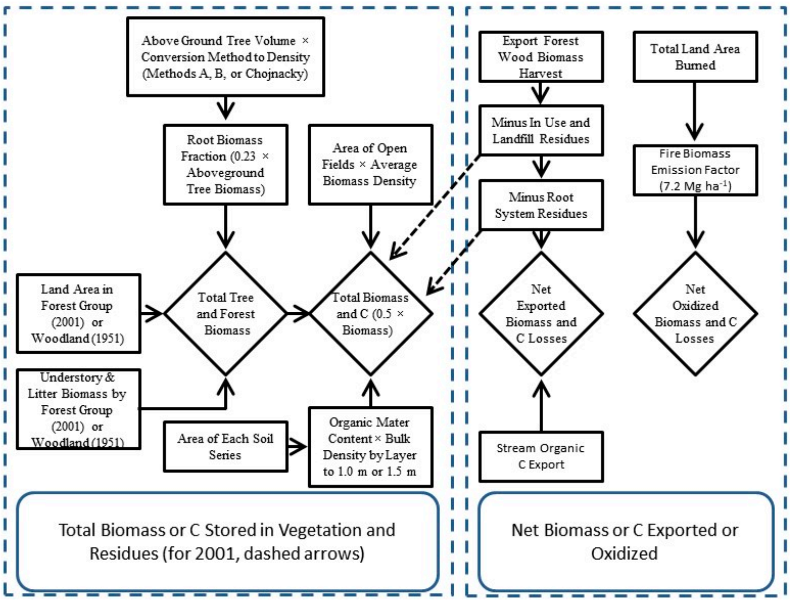

Figure 2. Biome biomass and carbon (C) components in 1951 and 2001 and net biome production in 2001 following Lovett et al. [38]. Described in Sections 2.1–2.4 and SM.

2.3. Estimates of Annual Biomass Fluxes, Life-Cycle Residues, and Net Ecosystem Production

The principal C fluxes on SRS, exclusive of industrial operations, were removals associated with harvested wood products, losses associated with forest fires, and stream export. Detailed descriptions of annual biomass fluxes, life-cycle residuals, and NBP estimation methods can be found in the supplementary methods (SM). Briefly, annual harvest and prescribed fire data covering the period 1955 to 2000 (provided by the United States Forest Service Savannah River) were used to estimate C fluxes associated with these management activities. Removal of total organic C (TOC) from SRS in stream water was estimated from literature values, as there were few continuous stream flow data coupled to TOC measurements available for SRS, and most of the major SRS streams had large contributing areas off SRS ([25], Table 2.7).

Root biomass remaining in soil immediately after tree harvests was calculated based on the harvest volume data. Residual root mass remaining each year after harvesting was calculated using a decay function ([39], $k = 0.0534$). In-use or landfill residues of stored C in 2001 from wood harvested for each year beginning in 1955 were determined ([22], Table 6) and summed to the year 2001.

The net biome production (NBP) follows the definition established by Kirschbaum et al. [40] to represent long-term changes in organic C, including exports, catastrophic losses and removals for large heterogeneous areas, but not animal organic C. Figure 2 provides a conceptual model of our approach for NEP. The form of the equation, following Lovett et al. [37], was estimated as:

$$\mathrm{NBP} = \Delta \mathrm{C_{org}} + \mathrm{E} + \mathrm{O_x} - \mathrm{I} \quad (1)$$

where ΔC_{org} is the change in organic C stored in ecosystem pools between 1951 and 2001, including vegetation and soils; E is the organic C exported during that period, stream losses and tree harvests minus in-use and landfill residues; O_x is the organic C oxidized during that period, fire losses; and I is the organic C imported during that period, none [38].

2.4. Soil Organic Matter and Carbon

Although the SOM content in old farm fields in 1951 and 1980 were reported [41], there was no method for reconstructing SOC for the entire landscape in 1951. We estimated SOC for 2001 based on the SRS-wide soil survey made by the Natural Resources Conservation Service (NRCS) [42] and NRCS databases, which provide values of soil geochemical and physical properties of representative pedons for most series (http://soildatamart.nrcs.usda.gov/). An additional objective of this study was to evaluate the potential bias in soil databases used to estimate soil C. Detailed descriptions of SOM and SOC estimation methods can be found in the supplementary methods (SM).

3. Results

3.1. Land Use Change

The total land area in 2001 was 80,174 ha, with forests comprising 73,824.4 ha and the industrial infrastructure, cooling water lakes, and rights-of-way occupying 6349.6 ha (Table 1). The difference in the total area between 1951 and 2001 reflects the land transfer between the SRS and the local county governments. The land use change on the SRS has been substantial. The agricultural land that existed in 1951 was converted to forests over the ensuing decades, resulting in an increase in the forested land area from 48,714 ha in 1951 to 73,824 ha in 2001; an increase of approximately 51%. The increase in the forested area occurred on 77% of the total area of agricultural lands in 1951.

3.2. Estimates of Forest and Non-Forest Biomass

Growing stock in 1951 was extremely low for pine and pine plantation woodlands and for the hardwoods and swamp woodlands. Depending upon the method used to calculate the total woodland biomass in 1951, the amount was estimated to fall between 1.73 Gg (Table 2) and 3.03 Gg (Table 3). The forest biomass density in 1951 was 35.6 Mg ha^{-1} and 62.2 Mg ha^{-1} for Method A and B, respectively. Method A generated lower values than Method B for the same amount of growing stock in 1951; however, when these two methods were applied to the 2001-inventory, we found similar values of 18.3 Gg (Method A) and 17.8 Gg (Method B), and they resulted in corresponding total biomass densities of 240.0 Mg ha^{-1} and 231.4 Mg ha^{-1}, respectively. Based on the average values for each inventory, the total forest biomass density increased by a factor of approximately 4.8 and the total biomass increased by 7.6. Although tree growth accounted for most of the increase in the biomass density, the higher measured values for understory dead and live materials in 2001 compared to the estimates for 1951 also influenced the biomass density. The increase in the total forested area accounted for the balance of the increase in the total biomass.

Table 2. Forest vegetation biomass density and total biomass estimates for softwoods (s) and hardwoods (h) for 1951 and 2001 using Method A [33], forest land area (Table 1) and forest understory values from (Supplementary Table S1) for 1951 and for 2001 [43].

Woodland Class	Area (ha)	Growing Stock (m^3 ha^{-1})	Aboveground Biomass Density [2] (Mg ha^{-1})	Root Biomass Density [3] (Mg ha^{-1})	Understory Biomass Density [4] (Mg ha^{-1})	Total Biomass (Mg)
Pine + pine plantation [1]	24,323.0	12.9 (s) 0.0 (h)	9.5 0.0	2.2	20.0	770,655
Pine + pine plantation	3065.7	0.0 (s) 0.0 (h)	0.0 0.0	0.0	20.0	61,314
Hardwood + swamp [1]	20,709.9	4.7 (s) 21.4 (h)	3.5 22.3	5.9	11.5	893,225
Hardwood + swamp	615.7	0.0 (s) 0.0 (h)	0.0 0.0	0.0	11.5	7081
Total 1951	48,714.5					1,732,274
Pine plantation	50,025.1	155.0 (s) 33.7 (h)	114.1 35.0	34.3	24.3	10,395,124
Pine-hardwood	2197.5	79.0 (s) 85.2 (h)	58.2 88.6	33.8	23.7	448,809
Hardwood-pine	2167.1	81.7 (s) 160.7 (h)	60.2 167.1	52.3	23.7	657,185
Hardwood	16,732.5	26.2 (s) 191.4 (h)	19.3 199.0	50.2	21.1	4,846,660
Cypress-tupelo	2702.2	212.4 (s) 400.6 (h)	156.4 416.6	131.8	21.2	1,961,797
Total 2001	73,824.4					18,309,574

[1] Expansion factors are applied to the softwood (pine) and hardwood separately. Cypress is treated as softwood; [2] Includes non-merchantable material, dead trees and trees <2.54 cm DBH.; [3] Root biomass for the softwood, hardwood and dead trees compute as 0.23 times aboveground biomass.; [4] Understory biomass include dead and live materials, and small trees <2.54 cm.

Table 3. Forest vegetation biomass density and total biomass estimates for softwoods (s) and hardwoods (h) for 1951 and 2001 using Method B [34], forest land area (Table 1) and forest understory values form (Supplemental Table S3) and for 2001 [43].

Woodland Class	Area (ha)	Growing Stock (m^3 ha^{-1})	Aboveground Biomass Density [4] (Mg ha^{-1})	Root Biomass Density [6] (Mg ha^{-1})	Understory Biomass Density [7] (Mg ha^{-1})	Total Biomass (Mg ha^{-1})
Pine + pine plantation [1]	24,323.0	12.9 (s) 0.0 (h)	21.8 (+ 1.3) [5] 3.6	6.1	20.0	1,285,227
Pine + pine plantation [2]	3065.7	0.0 (s) 0.0 (h)	10.8 (+ 0.7) [5] 3.6	3.5	20.0	117,846
Hardwood + swamp [2]	20,709.9	4.7 (s) 21.4 (h)	4.7 (+ 3.7) [5] 45.2	12.3	11.5	1,601,704
Hardwood + swamp [3]	615.7	0.0 (s) 0.0 (h)	1.4 (+ 1.6) [5] 19.1	5.1	11.5	23,852
Total 1951	48,714.5					3,028,629
Pine plantation	50,025.1	155.0 (s) 33.7 (h)	98.2 (+ 6.0) [5] 43.0	33.9	24.3	10,275,156
Pine-hardwood	2197.5	79.0 (s) 85.2 (h)	46.4 (+ 6.5) [5] 102.4	35.7	23.7	471,891
Hardwood-pine	2167.1	81.7 (s) 160.7 (h)	48.5 (+ 8.3) [5] 152.7	48.2	23.7	609,909
Hardwood	16,732.5	26.2 (s) 191.4 (h)	18.9 (+ 8.2) [5] 188.2	49.5	21.1	4,784,491
Cypress-tupelo	2702.2	212.4 (s) 400.6 (h)	188.1 (+ 5.1) [5] 295.5	112.4	21.2	1,681,687
Total 2001	73,824.4					17,823,134

[1] Values computed for the softwood gross cubic volume to mass. Mass for hardwoods is the intercept value for the zero volume; [2] Values computed for the hardwood and softwood (cypress) gross cubic volume to mass; [3] Values computed based on the no growing stock volume for hardwoods or softwood. Estimated mass are equation intercepts; [4] Values computed for the mass show softwood (including cypress) and hardwood estimated separately per ([34], Tables 9 and 10); 5 Biomass of the dead trees (+) calculated using the aboveground live tree biomass per ([34], Table 6); 6 Root biomass for the softwood, hardwood and dead trees compute as 0.23 times aboveground biomass; [7] Understory biomass include dead and live materials, and small trees <2.54 cm DBH.

The amount of non-forest biomass in 1951 was 5.6 Mg ha^{-1} times the area of abandoned crop and pasture lands (32,279.4 ha) or 180,765 Mg. This amount was only 7.5% of the average estimated woodland biomass in 1951. Reforestation of the fields, pastures, and industrial development reduced the amount of open land to approximately 2448 ha (Table 1). The amount of vegetation biomass in this area is therefore estimated to be approximately 5.6 Mg ha^{-1} times 2448 ha, or 13,709 Mg, which is less than 0.1% of the total vegetation biomass.

The total forest biomass density estimates for 2001 determined by the application of the national biomass estimator allometric equations [36] was 192 Mg ha^{-1} (Table 4), which was a much lower value for the total tree biomass than the values obtained using Methods A and B (Tables 2 and 3). The differences occurred in both the pine plantation group and the hardwoods. However, the relative difference for pine plantations was only 12.5% less, whereas the relative difference for hardwoods, swamp-tupelo, hardwood-pine, and pine-hardwoods were 56.1%, 53.4%, 50.3%, and 53.8% less, respectively. These latter differences appear to be primarily related to the biomass densities predicted for live hardwoods in Methods A and B and for live softwoods in the cypress-tupelo group. The estimated mass of dead tress using Method B was also substantially larger than the calculated mass we determined for all forest groups except cypress-tupelo.

Table 4. Forest vegetation biomass density and total biomass estimates for softwoods (s) and hardwoods (h) for 2001 using the national biomass estimator equations [34], forest land area (Table 1) and forest understory values [43].

Woodland Class	Area (ha)	Aboveground Biomass Density [1] (Mg ha^{-1})	Root Biomass Density [3] (Mg ha^{-1})	Understory Biomass Density [4] (Mg ha^{-1})	Total Biomass (Mg)
Pine Plantation	50,025.1	101.7 (s) (+ 1.0) [2] 26.8 (h)	29.8	24.3	9,183,482
Pine-Hardwood	2197.5	51.2 (s) (+ 2.5) [2] 82.5 (h)	31.3	23.7	299,300
Hardwood-Pine	2167.1	57.5 (s) (+ 1.7) [2] 135.2 (h)	44.7	23.7	421,284
Hardwood	16,732.5	18.9 (s) (+ 1.9) [2] 163.6 (h)	42.4	21.1	3,085,473
Cypress-Tupelo	2702.2	127.0 (s) (+ 6.1) [2] 305.1 (h)	100.8	21.2	1,184,104
Total 2001	73,824.4				14,173,642

[1] Values computed for the tree mass are for softwood and hardwood species; [2] Biomass of the dead trees in parenthesis (+); [3] Root biomass for the softwood, hardwood and dead trees compute as 0.23 times aboveground biomass; [4] Understory biomass include dead and live materials, and small trees <2.54 cm DBH.

As a check on the estimates of live tree biomass generated by Method B, we calculated the biomass using equations fitted to all trees (softwoods and hardwoods), as the authors did not use regression methods to ensure that the sum of the individual softwood and hardwood components was equal to the total for each plot ([34], Table 5). The results for 1951, in terms of the total aboveground live and dead tree biomass, were within 2% for hardwoods and 6% for softwoods for the two methods of estimating biomass, with Method B yielding slightly higher estimates for both hardwoods and softwoods. For 2001, the total aboveground live and dead tree biomass estimates derived from the Smith et al. equations ([34], Tables 5 and 6) were only 80% of the value obtained when applying their equations for pines and hardwoods separately ([34], Tables 9 and 10). The two methods of Smith et al. generated essentially identical (<1%) estimates of the live and dead tree biomass. However, when using the Smith et al. equations ([34], Table 5), pine plantations were consistently lower in the predicted biomass, and hardwood-dominated groups were consistently higher in the predicted biomass. In addition, our method for estimating dead tree mass gave values that ranged from 0.85 to 2.5 Mg ha^{-1} for all groups, except the cypress tupelo. Smith et al. equations ([34], Table 6) predicted much higher dead tree mass for those same groups (4.6 Mg ha^{-1} to 8.0 Mg ha^{-1}) (Table 5). The net ecosystem productivity was determined for the period from 1951 to 2001. The total aboveground tree biomass (i.e., stems) was determined as the average value of Methods A and B for conversion of the growing stock in 1951. The total aboveground tree biomass (i.e., stems) in 2001 was determined using the average of Method A and B, and the national biomass estimator equations [34] separately. Values of the biomass converted to C using a factor of 0.5.

3.3. Estimates of Annual Carbon Fluxes and Life-Cycle Residues

Large quantities of C were removed from the harvesting, fire, and stream transport between 1951 and 2001, but large quantities of C were also retained in root residues and in-use and landfills over that period. Forest harvesting removed approximately 1340.3 Gg C during the period from 1955 to 2001. The average removal between 1991 and 2001 was about 37.2 Gg C year^{-1} (Figure 3). The amount of material sold annually varied considerably due to market conditions. The estimated biomass loss from prescribed fires and wildfires was 1054.1 Gg during the period between 1952 and 2001. The equivalent C loss to fires was 527.1 Gg C or about 39% of the removal resulting from harvests. In the ten years from 1991 to 2001 an average of 21.0 Gg C year^{-1} was lost (Figure 3). The amount of C exported by streams from the landscape since 1951 was about 202,288 Mg year^{-1}, or 10.1 Gg C, over the 50-year period. This amount is less than 0.5% of the total C exports from the SRS. The cumulative root mass C residues in 2001 that remained following the harvest between 1955 and 2001 was estimated to be 197.3 Gg C (Figure 3). The results show a sustained increase despite the fluctuations in harvest volumes over the period. The trend does not indicate a leveling-off or decline as long as harvests are maintained or increased. The amount of carbon remaining from the harvested material in 2001 that existed in-use or in landfills was 454.6 Gg of C (Figure 4). This amount is 34.7% of the harvested carbon. When the root carbon mass remaining in the soil was added to the in-use and landfill carbon, 49.3% of the harvested carbon remained in organic form contributing to the total carbon stored in 2001.

Table 5. The net ecosystem productivity was determined for the period from 1951 to 2001. The total aboveground tree biomass (i.e., stems) was determined as the average value of Methods A and B for the conversion of growing stock in 1951. The total aboveground tree biomass (i.e., stems) in 2001 was determined using the average of Method A and B, and the national biomass estimator equations [36] separately. Values of the biomass converted to C using a factor of 0.5.

		Total Vegetation Carbon Stocks (Mg)				Total Carbon Flux (Mg) [5]		
Conversion Method	**Year**	**Stems [2]**	**Roots [3]**	**Understory Dead and Live**	**Fields and Open Lands [4]**	**Harvested Wood**	**Prescribed and Wild Fire**	**Streams Total Organic**
A & B	1951	649,067	148,181	397,509	90,338	0	0	0
A & B	2001	6,643,604	1,524,876	864,697	6855	1,340,300	527,100	10,114
Net Change (Total C) [1]	(9,632,451)	5,994,537	1,376,695	467,188	−83,483	1,340,300	527,100	10,114
		62.2%	14.3%	4.8%	−0.8%	13.9%	5.5%	0.1%
Chojnacky	2001	5,058,638	1,163,487	864,697	6855	1,340,300	527,100	10,114
Net Change (Total C) [1]	(7,686,096)	4,409,571	1,015,306	467,188	−83,483	1,340,300	527,100	10,114
		57.4%	13.2%	6.1%	−1.1%	17.4%	6.9%	0.1%

Landscape	**Area (ha)**	**Net Ecosystem Productivity (Mg C ha^{-1} year^{-1})**	
		Methods A & B	**Chojnacky Equations**
1951 Total area	81,180.0	2.37	1.89
2001 Total area	80,915.0	2.38	1.90
2001 Forest and open	76,272.4	2.52	2.02

[1] Net change in C by component represents 2001–1951. The total net C change is in parenthesis. The percent contribution to the total C change is shown under the component C change; [2] Includes live and dead tree mass ≥2.54 cm DBH; [3] Root C is 0.23 times total aboveground tree C; [4] Includes agriculture lands in 1951 and open right of ways in 2001; [5] Cumulative losses in organic C from 1951 to 2001. Does not include about 3500 Mg removed as pine straw between 1991 and 2001.

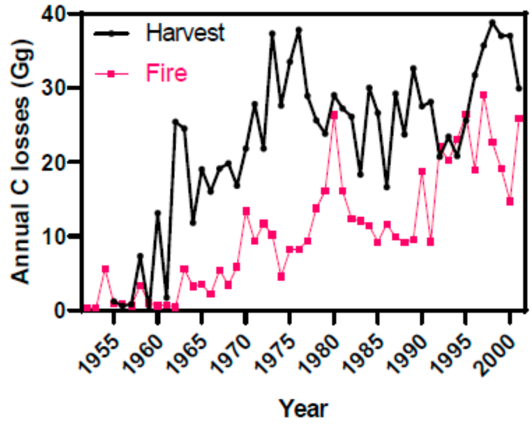

Figure 3. Annual carbon losses from the harvest removal (wood and bark) between 1955 and 2001 (thick dark line with circles) and from prescribed fires and wildfires between 1952 and 2001(thin light line with squares) at the Savannah River Site.

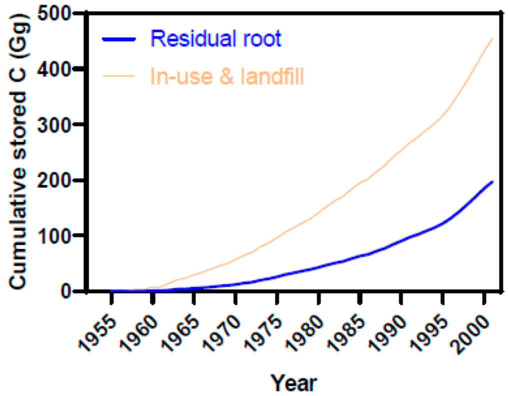

Figure 4. Cumulative stored carbon (C) remaining at the Savannah River Site in 2001 from residual root systems remaining after the harvest (thick dark line) and from in-use and landfill deposits (thin light line).

3.4. Estimate of NBP between 1951 and 2001

We calculated NBP over the 50-year interval with two approaches to provide estimates as a function of the methods for calculating the aboveground tree biomass (Table 5). The NBP varied only slightly depending upon the base area of the SRS landscape used. The largest NBP was 2.5 Mg C ha^{-1} year^{-1} using the 2001 vegetation area and the combined Method A and B to calculate the tree biomass. The lowest NBP (1.89 Mg C ha^{-1} year^{-1}) resulted from use of the 1951 land area and the national biomass estimator equations [36]. The largest uncertainty on NBP estimates resulted from the method for calculating the aboveground tree biomass. Between 70% to 75% of the NBP was dependent on the above- and belowground tree biomass estimates (Table 5). The understory dead and live C and fluxes of C from fire accounted for between 4.8% to 6.1% and 5.5% to 6.9% of the NBP, respectively. The harvested wood C was the largest export, accounting for 15.7% of the NBP. In contrast, the stream organic carbon export was very small, accounting for only 0.1% of the NBP.

3.5. Mineral Soil Carbon and Total C Stored in Vegetation and Soils in 2001

The amount of total SOC stored in 2001 ranged from 72.7 Mg C ha^{-1} (1.0 m) to 100.0 Mg C ha^{-1} (1.5 m) (Table 6). An additional increase in the SOC of 25% occurred by increasing the depth of calculation to 0.5 m. This increase in C below 1.0 m is consistent with the SRS environmental baseline studies (Figure 5). Frequently flooded or wetland soils contained approximately 56% of the total SOC under forests cover but occupied only 15% of the landscape when compared to the upland soils. The SOC density in frequently flooded soils was over seven times higher as upland sites.

Table 6. Total C stored in vegetation and soil components in 2001 using Table 4 for the biomass, and the NRCS soil C values. Described in Section 2.4.

Vegetation Group	Area (ha)	C (Gg)	C Density (Mg C ha^{-1})
Pine plantations [1]	50,025.1	4591.7	91.8
Mixed pine and hardwood	4364.6	360.3	82.5
Hardwoods and Cypress-tupelo	19,425.7	2134.8	109.9
Open areas/right of ways	2448.0	6.8	2.8
Subtotal Vegetation	76,272.4	7073.6	93.0
Life Cycle Residues			
Forest products	73,824.4	454.6	6.2
Root systems	73,824.4	197.3	2.7
Subtotal Residues	73,824.4	651.9	8.8
Soils (depth)			
Upland forest (1.0 m)	62,710.3	2361.3	37.7
Wetland forest (1.0 m)	11,114.2	3053.5	274.7
Right of ways (1.0 m)	2448.0	131.2	53,6
Subtotal Soils (1.0 m)	76,272.4	5546.0	72.7
Upland forest (1.5 m)	62,710.3	3229.9	51.5
Wetland forest (1.5 m)	11,114.2	4214.9	379.2
Right of ways (1.5 m)	2448.0	181.2	74.0
Subtotal Soils (1.5 m)	76,272.4	7626.0	100.0

[1] Pine plantations include loblolly, longleaf, and slash.

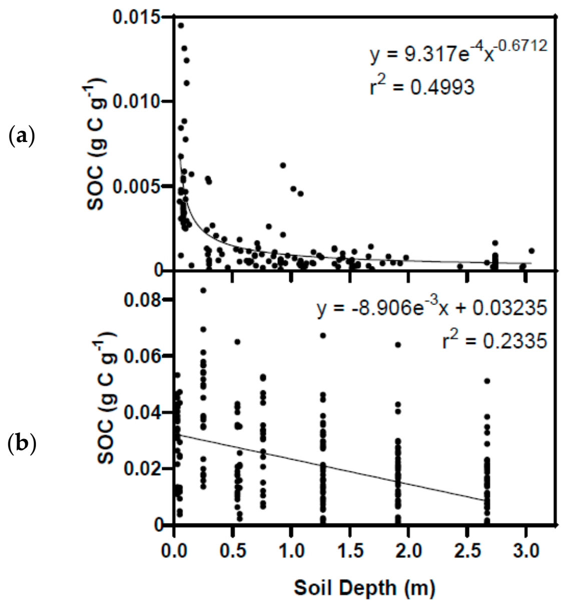

Figure 5. Soil organic carbon concentration with depth from SRS environmental samples collected and reported for (**a**) upland soils [44] and (**b**) wetland soils [45].

Site-specific environmental baseline samples for the upland soils were significantly lower ($p = 0.0167$) in the SOC (38.9 Mg C ha^{-1}) than estimates for the same soil groups or series using the NRCS databases, (58.7 Mg C ha^{-1}). The average difference between the samples and estimates was

19.8 Mg C ha^{-1}. In contrast, we observed no difference (p = 0.1556) in SOC for wetland/frequently flooded soils derived from site-specific environmental baseline samples and estimates from the NRCS databases, respectively (577.4 Mg C ha^{-1} compared to 557.6 Mg C ha^{-1}).

4. Discussion

4.1. Carbon Stocks & Fluxes after 50 years of Afforestation

The SRS reforestation program in the 1950s is representative of major regional efforts during the mid-twentieth century in southern USA that were designed to establish trees on less productive agricultural fields and cutover forests [5]. The data from our study are unique in that detailed records of vegetative conditions on abandoned fields and woodlands are typically not available for most land areas across this time period. Prior to 1951, the agrarian change and clear-felling of this particular landscape were substantial. The growing stock volume at SRS in 1951 was approximately one-half of the average growing stock reported in 1947 for the two major counties that contain SRS [46]. Pine woodlands demonstrated a more acute impact of the latter harvesting (Tables 2 and 3). The area in agriculture was typical for the region and, along with timber removals, represents the enormous loss in C stocks following conversion of the native forests [47,48].

Fifty years of afforestation and management had profound impacts on the landscape. In 2001, the total aboveground tree biomass and C was greatest in the Pine Plantation group (~65%) followed by the combined Hardwood and Cypress-Tupelo groups (~30%) (Tables 4 and 6). In contrast, the biomass density was largest in the Cypress-Tupelo group, followed by the Hardwood group, whereas the biomass density was lowest in the Pine Plantation and Pine-Hardwood groups. These differences in the biomass density reflect the combination of site productivity and management [25,28]. The pine plantations are typically located on less productive upland soils and the combination of clearfelling and thinning results in less standing biomass across the landscape. The swamps and riparian areas are more productive and have received limited harvesting. The ability to compare our biomass and C estimates between SRS in 2001 and other forest landscapes of similar scale in the region are limited. Data from the US National Forest have been published for the USA [18]. The C density we calculated for 2001 (174.4 Mg C ha^{-1}, Table 6) is slightly larger than the National Forest southern region average (160. 2 Mg C ha^{-1}) but falls within their 95% confidence interval of that average (74 Mg C ha^{-1} to 280 Mg C ha^{-1}). As a result of the differences in how individual C components were calculated, it is not possible to make more detailed comparisons with National Forest C estimates. We extracted FIA data on C for the SRS area using their online calculator to make a comparative estimate [49]. The FIA system lacks geospatial resolution because the locations of the FIA inventory plots are deliberately distorted and spatial estimates are limited to county-wide designations or simple variable circular areas in increments of 5 km. We approximated the center of SRS and used a radius of 15 km and 20 km which incorporated 29 plots and 44 FIA plots, respectively. In the latter radius, at least six (6) plots were outside the ownership boundary. For 2010, when the data was last updated, the FIA derived total non-soil C density was 93.3 Mg C ha^{-1}. This value was similar to our estimate for 2001 for the forest non-soil C density of 96.0 Mg C ha^{-1} (Tables 4 and 6). However, unless the FIA plot data are directly accessible and can be aligned with ownership boundaries, they can only provide an approximation of C stocks for landowners.

The NBP between 1951 and 2001 is related to both the forest growth and the various fluxes that contribute to the loss of C from the SRS (Table 5). Our NBP estimates varied largely as a result of the method for determining the aboveground tree biomass in 2001 and were less sensitive to the total area, but the conversion of land to the industrial infrastructure did reduce NBP. Using consistent methods to convert growing stock in 1951 and 2001 generated values in the range of about 2.4–2.5 Mg C ha^{-1} year^{-1}, whereas using direct conversion from national biomass estimators for 2001 generated much lower values (about 1.9–2.0 Mg C ha^{-1} year^{-1}). These values fall in the range reported in the region by other authors [50]. The more conservative C sequestration rate is close to the temperate forest mean of 1.9 Mg C ha^{-1} $year^{-1}$ for forests in the same age range and in the same region [3,51]. The stream export of organic C is very small relative to the other fluxes. Although the method used to derive the estimate are approximate, the value is consistent with a single watershed study at SRS, which calculated a loss of 2.3 g C m^2 $year^{-1}$ [52]. The largest flux was the removal of timber and accounted for 13.9%–17.4% of the NBP for the period. The wood harvested since 2001 has increased significantly. It is about 198,000 m^3 $year^{-1}$, or about 57 Gg C $year^{-1}$, which underscores an increased effect of this component on future NBP and C stocks. The impacts of the prescribed fire on NBP between 1951 and 2001 were much less than wood harvests (5.5%–6.9%). However, an effective prescribed burning program was not initiated until the late 1970s and the goal since 2005 has been to increase the area of prescribed burning by 30%–50% and reduce the interval between fires to 2–3 years to foster the pine savanna habitat required for the recovery of the red-cockaded woodpecker (*Dryobates borealis* Vieillot) [53]. Prescribed burning has since increased to over 9000 ha annually, with an equivalent C loss of over 30 Gg C $year^{-1}$. As a consequence, both the harvesting and fire will have a larger impact on NBP in the future. As a result of the detailed survey data on the understory and forest floor materials, we were able to directly estimate the biomass and C in this component (Table 5). Our average biomass and C values are similar to previous published estimates in the region for the broad pine and hardwood types [54]; however, our data suggest that this component is very dynamic and varies directly with the stand age, stocking, and fire frequency [43]. Data from the SRS 2010 inventory has already demonstrated a reduction in the forest floor and understory biomass in large areas experiencing an increase in fire frequency [55]. The national FIA program measured C in the forest floor material directly in the region and their average for South Carolina was about 15% less than ours [56]. Although within the range of error, we believe that the difference between the FIA measured C content and our conversion factor of 0.5 may partially account for this difference [57]. We would expect that the understory and forest floor layers will contribute less in the future to the NBP and C stocks at the SRS as a result of an increased age of the stands and the application of prescribed fire.

The C stocks in 2001 illustrate the large contribution of trees relative to other components and the vegetation in open areas (Table 6). However, the cumulative contribution of non-tree stocks is important. Life-cycle residues from forest products harvested over the prior decades contributes about 5% of the vegetation C stocks (Figure 4). If the root system, in-use, and landfill residues are added together, they represent almost 50% of the C removed in wood products, and thus substantially reduce the impact of forest product removals. Consequently, the impact of wood products harvesting and prescribed burning on the biomass and C losses and stocks are similar. This result has important implications when making holistic assessments of C balances from alternative forest management scenarios. We are not aware of other C balance studies in which the root system residues following harvests have been included. Previous research conducted on pine systems in the region shows that the decay rates of root systems are slower than the tree bole rates, perhaps as a result of resins and other decay inhibiting factors in pine roots [39].

4.2. Comparison of Methodological Approaches

We found important differences in the aboveground tree biomass and C estimates in 1951 between Methods A & B (Tables 2 and 3). These differences are related to the very low stocking conditions in 1951 and the assumptions inherent in each method. Method A assumes a simple linear relationship between the growing stock and aboveground tree biomass, whereas Method B is non-linear. The latter has a non-zero intercept that allows for an appreciable amount of non-merchantable biomass when the growing stock is low. We believe these differences were not apparent in 2001 when the growing stock volumes where much greater. This 2001 result is consistent with the regional comparison of the two methods [34]. Smith's equations for the biomass in 1951 that were based on combined hardwoods and softwoods volumes gave results very similar to the equations for hardwoods and softwoods separately (Method B). In contrast, we observed large differences between the equations when applied to the 2001 growing stock using Smith's combined equations compared to the separate equations for hardwoods and pines (Method B). We checked the results by using different forest classifications, e.g., Smith's natural pine compared to pine plantations, but the results were consistent. We believe the difference is related to the fact that the latter authors did not use seemingly un-related regression methods to ensure the separate hardwood and softwood equations were constrained by the total biomass.

Although Smith's combined equations and the use of the Chojnacky et al. [36] national biomass estimator equations generated a similar total biomass in 2001, they differed substantially in detail. Smith's equations were based on the national biomass estimators from Jenkins et al. [35], which were subsequently updated [36]. The softwood live tree biomass was lower using the Jenkins' derived biomass and the hardwood biomass was much larger. Various changes in the manner in which the national biomass estimator equations were developed for the species groups by Chonacky et al. [36] account for these differences. The relative increase in the softwood biomass we observed, was also found when the updated equation predictions were compared to the original Jenkin's equations at the regional level [18]. The differences between the hardwood and softwood C estimates using different methods will be important in detecting the total aboveground tree C changes in the future as the relative species composition within the landscape changes. Smith's equations also predicted larger amounts of dead tree biomass than our method, which was based on local data and was conservative because we did not adjust for stem breakage. Although dead trees were a small portion of the SRS biomass and C storage in 2001, the amount has more than doubled in the 2010 inventory due to the forest age [58]. The importance of dead standing trees varies by region, forest composition, age, and with catastrophic events such as fire, insects and disease [50]. Given its potential importance, a more accurate and consistent approach is required.

4.3. Soil Organic Carbon

The average upland SOC density to 1 m across the vegetative landscape at SRS is less than the SOC values estimated for the longleaf, loblolly, oak-pine, and oak-hickory broad forest types in the southern region, but slightly higher than the regional estimate for the oak-gum-cypress using similar databases and methods [18]. The SOC density for a large number of longleaf pine soils sampled to 1 m in the region varied from 32 Mg C ha^{-1} to over 98 Mg C ha^{-1} with the site quality and sub-region accounting for the largest source of variation [59]. The Rapid Carbon Assessment program data is the largest and most current information on the SOC density to 1 m depth that exists in a spatially explicit format covering the SRS [12]; however, the data could not be accessed directly and only the range of the SOC density in published gridded maps were available. These coarse map projections provided a range of values that included the average of SRS. Models have identified four main variables to predict the SOC, region, land use and land cover, main horizon, and textural class [60]. However, in the absence of the specific parameters for the applicable region, it is impossible to make a comparative assessment. The SOC in the SRS mineral soil accounted for 41.6% to 50% of the total C stocks in 2001 when considering soil depths of 1.0 m and 1.5 m, respectively (Table 6). The potential storage of additional SOC below these depths suggest that these values are conservative (Figure 5). Other studies have also identified the additional C stored in soils between 1 m to 3 m can, on average, increase the soil C storage in the temperate forest by 31%–41% [61]. The SRS environmental baseline samples collected to a depth of 3 m demonstrate that some wetland soils have considerable C stored below 1 m. Therefore, the SOC is the major stock of the total C stored on the landscape and it is concentrated heavily in wetlands, which occupy only 15% of the landscape. The SOC values in the NRCS regional soil databases and the SRS environmental baseline samples for these wetland soils were similar with no significant difference to 1.5 m. These wetland or frequently flooded soils also do not appear to have lost SOC due to agricultural tillage, although records indicate that at least some of these soils were cleared of forest and farmed.

The comparison of the estimated SOC stocks from the NRCS regional soil databases with the SRS environmental baseline samples in the uplands supports the previous studies that the upland SOC levels have not recovered from prior agricultural land use [62]. The difference in the SOC between the two groups suggest that a deficit of 19–20 Mg C ha^{-1} may have existed at the time of sampling, approximately 30 to 35 years post-agricultural. Remnant forests (i.e., no prior evidence of tillage or agrarian use) at SRS are small in size, generally 0.1 to <10 ha, and cannot be confirmed by the forest cover in 1951 alone. It is likely that most of the upland SRS environmental baseline samples were collected on old farm fields in 1951 or previously abandoned fields. Worldwide studies suggest that between 42%–56% of the SOC can be lost following cultivation [63]. Systematic declines in the SOM during old farm field succession SRS between 1951 and 1978–1980 have been documented [37,41], which suggests that pine plantings had little or no positive effect on the SOC sequestration during that initial 30-year period at SRS. The meta-analysis of the SOC accumulation rates in conversions from agriculture to plantations in the warm temperate moist forest of southeastern USA show a wide range in estimated rates, ranging from –14 g C m^2 $year^{-1}$ to 28 g C m^2 $year^{-1}$ [64]. The average of the 11 studies is 8.3 g C m^2 $year^{-1}$, which results in only 4.2 Mg C ha^{-1} accumulation in 50-years. Results from another study in South Carolina also demonstrated a low rate of the SOC accumulation following 50 years of pine plantation afforestation, with increases in SOC at surficial soil layers and losses at deeper soil layers [65]. The most recent data from the latter study shows that surficial soil layers continue to gain SOC, whereas the SOC in deeper layers has stabilized [23]. After 50 years, the mean SOC on 1951 post-agricultural longleaf pine plantations on two soil series was about 8 Mg C ha^{-1} less in the top 15 cm when compared to the adjacent stands of the longleaf pine that were forested in 1951 [66].

Although it is difficult to establish the current absolute deficit, the results of these studies suggest that there are significant opportunities for the SOC sequestration in post-agricultural upland soils at SRS. We believe that the potential for additional SOC sequestration is important in the restoration of longleaf pine ecosystems in the region because both the habitat for red-cockaded woodpeckers and the grass-herb understory is improved at very low pine and hardwood overstory stocking levels [67]. These low target stocking levels are typically 1/5 to 1/2 of managed pine plantations resulting in a loss in overstory C stocks [7,59]. The C stocks in the forest floor will be further reduced by frequent prescribed burning [68]. Relatively nothing is known about the potential for native savanna grasses to increase SOC. Indeed, an improved understanding of managing savanna systems to promote the SOC accumulation in a way that offsets the requisite reduction in the aboveground C stocks represents an important research priority for forest management in southeastern US, and other areas with analogous savanna systems (e.g., ponderosa pine savanna in western US and oak-hickory savanna in the midwest US).

5. Conclusions

The SRS offers a unique opportunity to assess C stocks and fluxes on a complex managed landscape over time, and to partition the components in a manner that enables an understanding of the impacts of active forest and land management practices on the net C sequestration processes. The data provides a solid baseline for 2001 and the opportunity to sustain or mitigate changes in C in the future. Four land and forest conditions are expected to dominate the landscape and influence the future landscape C balance. Wetlands and frequently flooded areas store a large fraction of C on just 15% of the landscape, and because of wetlands protection, equipment operation limitation and required stream-side buffers in forestry, the stocks will likely remain unchanged or increase slightly as forests mature. Approximately 27,000 ha is managed for the longleaf pine savanna using fire and, as a result, the vegetation C stocks are expected to decline substantially in the future. For these systems to regain the carbon balance of a plantation forest, a shift in the C accumulation from above- to belowground must occur. To what degree the additional SOC sequestration potential on prior-agricultural soils may offset this decline is unknown. A net increase or decrease in the facility and infrastructure will also have a substantial impact. Some opportunities to grow non-woody bioenergy crops on a portion of the 2448 ha of the right-of-way lines may mitigate the effects, if SOC and other vegetation residues can be shown to enhance C stocks in these areas. With increasing age of the forested areas, NBP will decline as mean annual increment declines, making reliable estimates of C stocks and fluxes more important. In 2009 and 2018, the SRS shifted its inventory approach to a LiDAR based system with a large number of precisely located calibration plots to meet the overall management needs [68]. However, the conversion of 'wall-to-wall' spatially explicit data to C stocks is a challenge because of the complex species composition and stand structure, and the methodology has yet to be developed for these complex systems.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/10/9/760/s1, Table S1: Crosswalk between source and values of understory dead and live biomass for combined woodland class areas in 1951, including non-stocked areas. Table S2: Crosswalk between woodland classification in 1951 or forest groups in 2001 for applying equations to convert growing stock volume to aboveground live and dead tree biomass. Equation names refer to ownership and vegetation names for the SE Region. Table S3: Relationship between aboveground biomass taxa equations and species based on species assignments and numerical codes for species.

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