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USDA Forest Service, Southern Research Station

The Terrestrial Carbon Inventory on the Savannah River Site

Assessing the Change in Carbon Pools 1951-2001

Final Report

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Executive Summary

The Savannah River Site (SRS) has changed from an agricultural-woodland landscape in 1951 to a forested landscape during that latter half of the twentieth century. The corresponding change in carbon (C) pools associated land use on the SRS was estimated using comprehensive inventories from 1951 and 2001 in conjunction with operational forest management and monitoring data from the site. Carbon storage in forest biomass on the SRS increased over the 50-year period due to (1) conversion of agricultural land, which comprised approximately 40% of the original land, to forests, and (2) active management of the forest lands. The forest land has increased from 48,903 ha in 1951 to 73,836 ha in 2001. Approximately 9% of the SRS landscape is industrial land derived from a combination of the original woodlots and agricultural lands.

Total biomass C on the SRS was 512.6 Gg C in 1951, as of 2001 there was a total of 6,143.1 Gg C, reflecting an average accretion rate of 138.6 Gg C yr^{-1}, when harvest removals are included. Across the site, C stored in biomass in 2001 averaged 83.2 Mg C ha^{-1}, a significant increase from the 6.3 Mg C ha^{-1} average in 1951. Development of the forest floor added 312 Gg C; unfortunately, we were unable to estimate the change in the mineral soil C pool due to limitations in the available data. The 2001 soil C pool was estimated to be 124.0 Mg C ha^{-1}. Accordingly, the C stored in forest biomass in 2001 was approximately 40% of the total (soil and forest) C storage on the SRS.

Prescribed fire and harvesting are the two principal forest management practices affecting C accumulation in the SRS forests. Over the 50 year inventory period, approximately 569 Gg C was removed from the site through prescribed fire. The loss of C as a result of fire is through partial consumption of understory biomass and forest floor. Most of the losses due to fire occurred between 1978 and 2001. Carbon loss to wildfire over the 50 year period was 18 Gg C, approximately 3.1% of the total C loss to fire. Harvest removals accounted for a total of 1302.8 Gg C over the inventory period. Harvest removals over the last 10 years (1991-2000) averaged 37.1 Gg C yr^{-1}, reflecting increased harvesting associated with sustainable management of the SRS landscape. Export of C from the SRS in stream runoff was a small amount, approximately 2.1 Gg C yr^{-1}. The net ecosystem productivity, an integration of the changes in C pools and fluxes over the 50 year period was 162.4 Gg C yr^{-1} or 2.2 Mg C ha^{-1} yr^{-1}.

The utility of the SRS forest inventory and operations data for landscape-scale assessments was demonstrated using Forest-DNDC; in turn the model was used to assess metrics, such as greenhouse gas fluxes, that couldn't be obtained through the inventory or operational monitoring data. Forest-DNDC was able to accurately simulate the change in forest biomass over the 50 year period. The model performance efficiency ($E \leq 1$) was 0.96 for the forest biomass predictions, and 0.91 for harvest and 0.38 for fire removals. The simulated average net ecosystem exchange (NEE) (1.65 Mg C $ha^{-1}yr^{-1}$) approximated the average C sequestration to wood biomass (1.54 Mg C $ha^{-1}yr^{-1}$) over the 50-year inventory period. The simulated fuel mass was consistent to the inventories, 2.2 vs. 2.4 Mg C ha^{-1} for 1951 and 12.2 vs. 12.9 Mg C ha^{-1} for 2001, respectively. Loss of C through soil respiration was estimated to average 2.84Mg C ha^{-1} yr^{-1} (10.4 Mg CO_2 ha^{-1} yr^{-1}). Methane flux based on the model simulation indicated that the wetlands on the SRS are a substantial CH_4 source, estimated at 358 kg C ha^{-1} yr^{-1}; however, the uplands are a CH_4 sink, consuming approximately 0.1-10 kg C ha^{-1} yr^{-1}.

Table of Contents

page

1. Introduction

The Savannah River Site (SRS) (Fig.1) is an ideal location to assess carbon (C) sequestration associated with operational forest land management. The site is a large landscape mosaic (>80,000 ha) consisting of uplands (80%) and wetlands (20%), with complex topographic and hydrological characteristics, and it has a well-documented history of forest land management over a 50-year period. Consideration of the effects of forest management activities on the terrestrial C balance is particularly important in the southeastern US, where the effects of routine management and reforestation of prior-converted agricultural land is central to the considerations of climate change and mitigation of global warming. The Savannah River Site represents a unique opportunity because of the documented land use over the past 50 years (Kilgo and Blake 2005).

The objective of this project was to assess the changes in the C balance on the Savannah River Site from the time the property was acquired by the U.S. Government in 1951 until 2001, when a comprehensive forest inventory was conducted. This report is in response to Executive Order 13514 (http://www.fedcenter.gov/programs/eo13514/) which calls for a carbon inventory of federal lands. In developing the assessment we followed the IPCC standards for carbon management (Nabuurs et al. 2007).

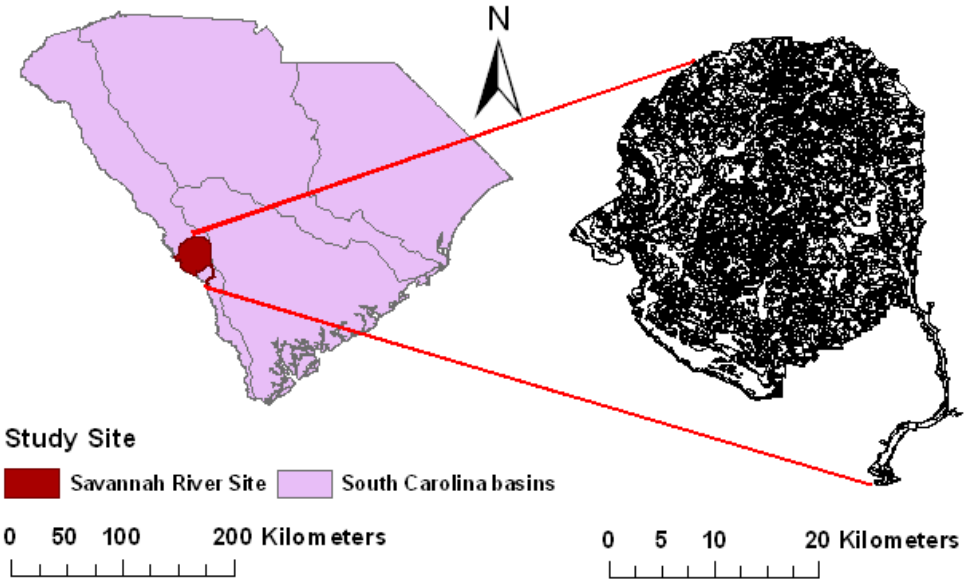

Fig. 1. Location of the Savannah River Site within South Carolina

Detailed forest inventories in 1951 and 2001 provide a unique basis to assess the changes in C stocks over the 50-year period, and detailed operational records permit the assessment of C fluxes associated with forest management activities. Our approach was to utilize the two inventories to create a balance sheet of C stocks at the two time periods. Because those inventories were concerned with land and forest resources, the C content was estimated based on well-established norms. Fluxes associated with forest management (e.g., prescribed fire, harvesting) and losses in stream water were derived from estimates based on operational databases. This approach facilitated an aggregated assessment of the C stocks across the entire site, excluding current industrial areas and water bodies. The size of the assessment area, the long time period between inventory periods, and the high quality data are highly unusual for this type of assessment. We also include an assessment of harvested product life cycle to provide additional context for considering entirety of C fluxes derived from the site. Accordingly, the findings from this work provide a basis to assess the cumulative effects of landscape-level management on forest C pools.

2. Data and Methods

2.1 Source Data

2.1.1 The 1951 Inventory

A complete inventory of the land that was acquired to develop the Savannah River Site was conducted in 1951 (U.S. Army Corps of Engineers, 1951). The inventory included records of land use, timber volume and ownership-parcel maps. The data have been synthesized and used in conjunction with an ortho-rectified mosaic of aerial photos from 1951 for a variety of studies (Savannah River Site Operation Office, 1959; Sumerall and Lloyd, 1995; White, 2004). The tabular and spatial data from the inventory were provided in electronic format for this study by the U.S. Forest Service Savannah River (USFS-SR).

The 1951 inventory was parcel-based (Fig. 2). The tract comprised 1,394 parcels, with parcels ranging in size from 0.04 to 2,424.3 ha. Most of the parcels contained three dominant land use types: forest, crop and pasture. In 1951, the SRS had 48,903 ha of woodlands and 32,279 ha of agricultural lands that was comprised of croplands (30,984 ha) and pasture (1,295 ha). The woodlands were classified as pine, pine-plantation, hardwoods, swamp and ponds, although the

area of the individual cover types was not provided. Wood biomass for each cover type was divided into three product classes: saw timber (classified for pine, gum, poplar, miscellaneous hardwoods and cypress), pulp (classified for pine and hardwood) and fuel (mixed species). The wood volume in each parcel of forestland was reported as board feet for saw timber and as cords for pulp and fuel wood (see the conversion factors in Appendix A).

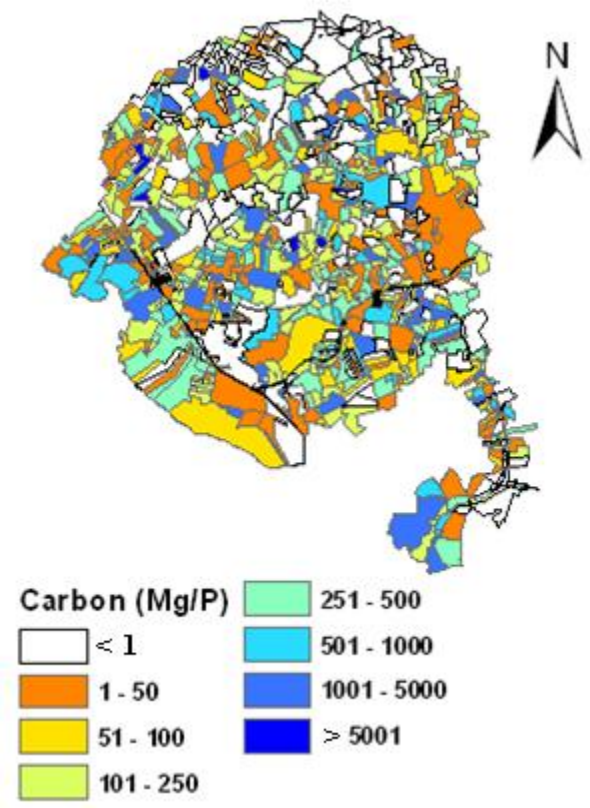

Fig.2. Total biomass C in parcels within the SRS in 1951. in 1951.

2.1.2 The 2001 Inventory

A detailed forest inventory of the SRS was conducted during March 1999 to January 2002 (Parresol, 2004). It was a sample-based inventory, using 629 plots to assess forest biomass pools on 72,089 ha of forest land. However, 1,746 ha forest land on the SRS was not included in the inventory. Forest biomass was assigned to product classes based on forest type; the classes were solid wood (≥9″ DBH for pine, ≥12″ for hardwoods), pulp wood (5.0-8.9″ and 6.0-11.9″ DBH for pine and hardwoods, respectively) and fuel (<5.0″ and <6.0″ for pine and hardwoods, respectively), and grass and shrub. In addition to above-ground biomass, the inventory measured forest floor mass which included coarse woody debris. For this study, the summarized biomass estimates from the 2001 inventory (Parresol, 2004) were used as the basis for the C inventory at SRS.

2.1.3 Fluxes

Inclusion of C fluxes is essential for assessing the change in C stocks on the SRS over the 50-year period. The principal fluxes, exclusive of industrial operations, on the site are removals associated with harvesting wood products, losses associated with forest fires, and losses in

stream flow. Consideration of CO_2 is not given here, because the change in biomass reflects the net sequestration.

2.1.3.1 *Forest Harvests*

Forest harvest activities on the SRS have been carried out since 1955, and summarized by Blake (2005). Data covering the period 1955 to 2000 were provided by the USFS-SR. The data consisted of annual forest harvest removals (m^3) aggregated as pine or hardwoods into two size classes: small round wood (SRW), 10-24 cm, and large round wood (LRW), >24 cm.

2.1.3.2 *Fire*

The area of prescribed and wildfire on the SRS was developed and supplied by USFS-SR (Shea and Bayle, 2005). The tabular data consisted of the area burned annually by prescribed and wild fires on the SRS. The prescribed fire area was divided among five types [planting site preparation, rough reduction, railroad ROW (adjacent to railroad line), RCW/wildlife (Red cockaded woodpecker), and other]; the distribution of the prescribed fire acreage among those types was approximately 8.6, 50.0, 1.8, 33.0 and 6.6% of total burned area during the period from 1952-2001. The area burned by wildfire during this period was a small fraction (approx. 3.1%) of the total burned area. There is no data on fuel loading and fuel consumption for the categories of prescribed fire and wildfire; therefore the mean fuel consumption (4.01 Mg C ha^{-1}) as determine from a meta-analysis of fuel consumption studies at the SRS (Goodrick et al., 2010) was applied to the annual burn acreage.

2.1.3.3 *Stream Export*

Loss of C in stream water was calculated using measured and estimated stream flow data on the SRS and C concentration data based on studies conducted on SRS streams. Stream flow data were obtained from the USGS water resources database (http://waterdata.usgs.gov/sc/nwis/rt). Since measured stream flow data was not available for the entire 50 year period, it was estimated using a computed relationship between precipitation and flow for each of the streams that were based on the available records. Precipitation data were obtained from the NOAA weather database for southeastern Aiken (http://www.ncdc.noaa.gov/oa/mpp/digitalfiles.html). Total organic carbon (TOC) in stream water on the SRS varies greatly, ranging from 1.0-13.2 mg l^{-1} representing variations in sampling locations, climatic factors and flow (Kolka et al., 2005a).

Fortunately, a comprehensive study by Dosskey and Bertsch (1994) provided a basis for estimating total organic C in stream water for use in this assessment. Accordingly, the total organic carbon in the water was estimated as particulate organic carbon (POC=1.8 mg l^{-1}) and dissolved organic carbon (DOC =5.3 mg l^{-1}). Those concentration values were applied to the annual flux each stream draining the site to estimate the total hydrologic C export.

2.1.4 Soil

Soil resource data for the site was available from two principal sources (see Appendix B), the site-wide soil survey made by the NRCS (Rogers, 1990) and site-specific studies made by Looney et al. (1990) for upland soils and by Dixon et al. (1997) for wetland soils. A digital copy of the soil survey was obtained from USFS-SR, and the data containing all parameters needed to estimate soil C for the soil types in this assessment area were obtained through the USDA-NRCS soil database (http://soildatamart.nrcs.usda.gov/). We attempted to augment the NRCS data with data from other on-site studies (Odum, 1960; McKee et al., 1983; Odum et al., 1984; Looney et al., 1990; Dixon et al., 1997; Smith, 2000; Sanchez et al., 2003); unfortunately, the scale and the number of soils considered by the on-site studies were too small to provide a basis for a site-wide assessment. An estimate of the soil C content for 2001 was calculated to a depth of 1.5 m for each of the soil types using the C content and bulk density from the NRCS national soils database.

2.1.5 Forest Floor

Coarse woody debris, litter and duff comprise the forest floor. The forest floor mass averaged 6.0 Mg ha^{-1} in 2001 (Parresol, 2004). Data on the forest floor mass was not available for the 1951 inventory. Since the 1951 landscape consisted of agricultural fields and wood lots with low stocking that were used for grazing (Blake and Bonar, 2005), we used an estimate (2.4 Mg ha^{-1}) based on grazed forest lands during the period (Hurley, 1950).

2.1.6 Land Area and Land-Use Types

The total land area in 1951 was 81,182 ha based on the parcel-based inventory provided by USFS-SR. Forestland was 48,903 ha (approx. 60% of the land at SRS), cropland was 30,984 ha, and pasture was 1,295 ha. The total land area in 2001 was 80,915 ha, with forests comprising 73,836 ha and the industrial land occupying 7,079 ha. The difference in total area between 1951

and 2001 (267 ha) reflects land transfers between SRS and local governments (J. Blake, pers. comm.). Those changes in allocation of land over the last 50 years are described by Blake and Bonar (2005). As mentioned in Sec. 2.1.2, the forest inventory was conducted on 72,089 ha of the 73,835 ha of forest on the SRS, and it also excluded the industrial area (which includes developed lands, open water bodies, roads and railroad right-of-ways).

2.2 *Calculations*

The following summarizes the calculations used for the C inventory at the two periods. The conversion factors used to obtain a C equivalent are presented in Appendix A.

2.2.1 Forest Types among the Inventory Periods

The forest inventory data on the SRS were grouped into four cover type classes to provide a basis for comparison among the two inventory periods (Table 1). For the 2001 inventory (Parresol, 2004), the biomass volume and density were reported by cover type. For the 1951 inventory, there wasn't direct correspondence between the reported wood volume and cover type acreage. The 1951 forest volume data was provided as sawlog volume for pine, hardwoods, gum and cypress classes, and pulp plus fuel-wood volume for pine or hardwood classes. The 1951 forest area was provided as the following cover type classes: pine, pine plantation, hardwoods, and swamp/ponds. Because of the incongruity between the classes used to report wood volume and forest area, the correspondence of the reported volumes to the forest area could be uncertain if the acreage wasn't provided. The following rules were used to address the inconsistency, on an individual parcel basis:

- If there was a reported volume for hardwood, but no reported acreage for hardwoods or swamps, the hardwood volume attributed to the pine cover type acreage;
- If there was a reported volume for pine, but an acreage wasn't reported, the pine volume was attributed to the upland hardwood cover type acreage;
- If there was a reported volume for gum / cypress, but not a corresponding acreage for swamps / ponds, then the volume was attributed to the hardwood cover type acreage.

Stocking density for the 1951 inventory was then based on the cumulative volume and area of each cover type.

Table 1. Cross-walk of the cover type classes reported in the 1951 and 2001 inventories, with the four cover type classes used for this assessment.

Cover type	2001	1951
Pine	Loblolly, Longleaf and Slash	Pine and pine plantations
Pine-hardwood	Pine-hardwood	
Upland hardwoods	Hardwoods and Hardwood-pine	Hardwoods
Lowland hardwoods	Cypress/Tupelo	Swamps / Ponds

2.2.2 Biomass Estimates

2.2.2.1 *Wood*

Two approaches were used to estimate wood biomass from the inventories conducted in 1951 and 2001. Initially, the functions developed by Smith et al. (2003), which are a set of empirical equations based on long-term Forest Inventory and Analysis (FIA) data, were used for the 2001 inventory. The live-tree biomass (L) in Mg ha^{-1} was estimated using Eq. 1:

$$L = F \cdot \{G + [1 - \exp(-V/H)]\}, \quad (1)$$

where F, G, and H are coefficients in the nonlinear regression equation (Smith et al., 2003); and V is wood volume (m^3 ha^{-1}). This equation can be used to estimate above ground biomass and it can also be applicable for estimating the total (including above- and below-ground) biomass, but the values of the coefficients are different (see Smith et al., 2003). The standing dead tree mass (D) in Mg ha^{-1} was estimated using Eq. 2:

$$D = L \cdot A \cdot \exp\{-[(V/B)^C]\}, \quad (2)$$

where L is live-tree mass density estimated using Eq. 1; A, B and C are coefficients in the nonlinear equation (Smith et al., 2003); and V is the same as that used in Eq. 1.

When the Smith functions (i.e., Eqs. 1 and 2) were applied to the 1951 inventory data, we found that the biomass was grossly over-estimated, presumably an effect of the 1951 inventory data being at the lower edge of the range considered by Smith et al. (2003). Eqs. 1 and 2 have a steep slope in the lower range; consequently a small change in V can result in a large change for L and D. Therefore, an established approach based on the relationship between the volume and weight for commercial product classes (timber & pulp) was used to estimate biomass for both inventories so that they would be assessed similarly (Wenger, 1984). To account for top-wood

(crown) biomass in the 1951 data, the ratio of commercial biomass to top volume provided in the 2001 inventory (Parresol, 2004) was used. The aboveground live tree biomass (L_{abg}) in Mg ha^{-1} was estimated as:

$$L_{abg} = V \cdot W \cdot (1+T) \quad (3.1)$$

where V is the given wood volume in m^3 ha^{-1}, W is the species conversion factor (Wenger, 1984, pp. 582-584) to convert volume in m^3 to biomass in Mg, and T is the coefficient of the tree top relevant to timber obtained from Parresol (2004). The values for T are 0.1356 for pine, 0.1793 for hardwoods and 0.2183 for bottomland hardwoods. The total live tree mass (L_T) in Mg ha^{-1}, which includes above- and below-ground biomass, was estimated as

$$L_T = L_{abg} \cdot (1+R), \quad (3.2)$$

where L_{abg} is obtained from Eq. 3.1; and R is the coefficient of roots relevant to aboveground biomass, 0.3 as reported by Schroth (1995) and IPCC (2003). The standing dead wood mass (D_T) was estimated as

$$D_T = L_{abg} \cdot D_w, \quad (3.3)$$

where D_w is the coefficient for estimating standing dead wood, which is 4% of live tree mass on a ha based on the mass ratio of standing dead tree to live tree estimated using Eq. 1 and Eq. 2 for the 2001 inventory data.

2.2.2.2 *Crop and Pasture*

The C stocks (C_S) of crop and pasture were estimated using the following equation:

$$C_S = A \cdot K, \quad (4)$$

where A is the area (ha) of crop or pasture; K is the stocking in Mg ha^{-1}, 3.32 and 2.39 for crop and pasture, respectively. The area of crop and pasture land was provided directly by from the 1951 land inventory. The crop and pasture biomass were estimated from the 1950 Agricultural Census for South Carolina (Hurley, 1950).

2.2.2.3 *Forest Floor*

Forest floor biomass (F_B) was estimated as

$$F_B = A \cdot M, \quad (5)$$

where A is the vegetation type-based area (ha); M is unit weight in Mg ha^{-1}, obtained from Parresol (2004) for 2001, and 2.4 Mg ha^{-1} (Hurley, 1950) for the 1951 inventory for all forested areas.

2.2.2.4 *Root Biomass after Harvesting*

The root biomass remaining in the soil after tree harvests was calculated based on the harvest volume data. Since we assumed that the root mass was 30% of the aboveground biomass (Schroth, 1995; IPCC, 2003), root biomass (R_M) left in soils as a result of harvesting was estimated as:

$$R_M = R \cdot (1+T) \cdot V \cdot W, \quad (6)$$

where R is the root:above-ground coefficient (0.3); T is the coefficient of the tree crown biomass, same as that in Eq. 3.1; V is harvested solid wood volume in cubic meter; W is the species conversion factor (Wenger, 1984, pp. 582-584) to convert volume in m^3 to biomass in Mg (also see Eq. 8) .

2.2.3 *Soil*

2.2.3.1 Soil Organic Carbon

Soil total organic C (SOC) within 1.5 meters deep soil was estimated as:

$$SOC=\sum C_i \cdot D_i \cdot B_i \cdot 10000, \quad (7)$$

where SOC is total C in a hectare area within 1.5-meter deep soil (Mg C ha^{-1}); C_i is the mean C content in ith soil layer (Mg Mg^{-1}); D_i is the thickness of ith soil layer (m) ($\sum D_i$=1.5 m); B_i is the bulk density of ith soil layer (Mg m^{-3} or g cm^{-3}) (Rogers, 1990). The total SOC in each type of soil was multiplied by the relevant area of the soil type. The total SOC in the assessment area was the sum of the total SOC in all soil types.

2.2.3.2 Comparison of SOC from Different Data Sources

The key parameters to calculate SOC are soil depth, C content, and bulk density (Db). However, the site-specific studies conducted by Dixon et al. (1997) and Looney et al. (1990) did not provide soil Db to estimate SOC. Accordingly, the Db (minimum, maximum and mean) from the NRCS database was used to estimate SOC for the soils from all data sources. Different soil thickness was also used to assess SOC, 1.5 m deep for upland soils and 2 m for wetland soils, respectively. In order to compare the differences in SOC from various data sources, the GPS values obtained from USFS-SR for SSS were projected to NRCS's soil map using ArcGIS 9.2 to obtain relevant soil type/series due to differences in carbon content among the types and series. The soil types obtained from the project were verified to check if the type determined by GIS was in agreement with the sample, especially for wetland soils. If the type from the map was different from the sample, the positioned location on the map would be manually moved within 30-50 m around the positioned location (manual verification). If the type was still not same and the soil classified as upland soil by SSS, an upland soil type within 30-50 m and the nearest the GPS position was used; if the soil was classified as wetland soil, a wetland soil type that was the nearest the GPS position was accepted.

2.2.4 *Fluxes*

2.2.4.1 Harvest

The harvested biomass (H) was calculated as

$$H = V \cdot W, \tag{8}$$

where V is harvested solid wood volume in m^3 provided by USFS-SR; W is the species conversion factor (Wenger, 1984, pp. 582-584) to convert volume in m^3 to biomass in Mg, 0.6299, 0.5726 and 0.5125 for pine, hardwoods and bottomland hardwoods, respectively.

2.2.4.2 Fire

Carbon loss to forest fire (prescribed and wild) was estimated using mean fuel consumption on the Upper Coastal Plain in South Carolina (Goodrick et al., 2010) using the following equation

$$C_F = A \cdot F_C, \tag{9}$$

where C_F is the carbon loss to fires; A is burned area (ha); F_C is the coefficient of fuel consumption (4.01 Mg C ha^{-1}) obtained from Goodrick et al. (2010).

2.2.4.3 Stream Flow

Riverine C loss (C_R) was estimated as

$$C_R = A \cdot P \cdot R_f \cdot C_x, \quad (10)$$

where C_R is the riverine carbon loss; A is the basin area in ha; P is annual precipitation in mm obtained from the NOAA weather database for southeastern Aiken, 1236 mm averaged from 60 years; R_f is the mean annual flow rate (annual flow to annual precipitation), 32.5% based on 68 observations of annual streamflow from four streams during the time periods without industrial operation influences, obtained from USGS water resources database; C_x is the organic C concentration in water, including particulate organic carbon (POC=1.8 mg L^{-1}), dissolved organic carbon (DOC=5.3 mg L^{-1}) and total organic carbon (TOC=7.1 mg L^{-1}) as reported by Dosskey and Bertsch (1994).

2.2.4.4 Root Decomposition

Root decomposition or life cycle was evaluated for roots mass remaining after the tree harvest. The exponential function (Ludovici et al., 2002) was defined as

$$WT_t = m_0 \cdot \exp(-ky), \quad (11)$$

where WT_t is the root mass remaining at time t; m_0 is the initial root mass obtained from Eq.6; k is the decomposition coefficient, 0.0534 is the total pine root decomposition rate given by Ludovici et al. (2002); y is the number of years since harvest. Therefore, the root C loss to decomposition in year t (L_D) was calculated as

$$L_D = WT_{t-1} - WT_t, \quad (12)$$

2.3 *Modeling Carbon Balance Using the Biogeochemical Model Forest-DNDC*

2.3.1 Model Description

Computer models can be effective tools and they have been widely utilized to assess atmospheric CO_2 sequestration in forest ecosystems. The development and application of a plethora of biogeochemical models with respect to estimating C sequestration to and greenhouse gas (GHG)

emission from ecosystems reflect their values, such as SPA (Williams et al., 1996), 3-PG (Landsberg and Waring, 1997), BIOME-BGC (Thornton et al., 2002), BIOMASS (Hingston et al., 1998), CABALA (Battaglia et al., 2004), Forest-DNDC (Li et al., 2000), PROMOD (Battaglia and Sands, 1997).

Forest-DNDC was employed to simulate the C dynamics on the SRS for the 50 year inventory period. Forest-DNDC is a process-based model using the soil C and N dynamic model DNDC (DeNitrification and DeComposition) (Li et al., 1992a, b; Li, 2001) with the forest growth model PnET (Aber and Federer, 1992). In order to evaluate C balance on a large forested land for a long time span, a modified version of the model was employed with a spatially explicit biogeochemical modeling approach (Dai et al., 2011). Through linking the outputs from GIS (Dai et al. 2011), the model can utilize spatial and temporal biogeochemical characteristics of study sites for predicting plant growth and production, C and N balance, generation and emission of soil-borne trace gases, and impact of forest management, including harvest, fertilization and thinning on C and N dynamics in forest ecosystems (Li et al., 2000; Stang et al., 2000; Li et al., 2004; Miehle et al., 2006). The model integrates decomposition, nitrification-denitrification, photosynthesis and hydro-thermal balance in forest ecosystems. It distinguishes the vegetation into three layers, overstory (dominant canopy), understory (low and short trees, may see as fuel wood) and ground growth (including grass and moss). The model has been tested and used for estimating GHG emission from forested ecosystems in wide climatic regions, including boreal, temperate, subtropical and tropical (Stang et al., 2000; Zhang et al., 2002; Li et al., 2004; Kiese et al., 2005; Kesik et al., 2006; Kurbatova et al., 2008; Dai et al., 2011). A detailed description of the model and the algorithms are given in Li et al. (1992a, b), Li (2001), Zhang et al. (2002), Li et al. (2004), and Cui et al. (2005).

2.3.2 Model Setup and Parameterization

Forest-DNDC with watershed scale modeling approach was configured to model C dynamics using spatial and temporal physical and biogeochemical characteristics for the SRS starting from 1950. The key parameters are presented in Table 2. The parameterization is based on the following. (1) SRS is over 80,000 ha in size in which the industrial areas and water bodies are heterogeneously scattered among the forest areas (~74,000 ha). (2) About 40% of the land was converted from agricultural area to forestland year-by-year after 1951. (3) Planting and

harvesting activities have been consecutively carried out since 1952 and 1955, respectively, which produced a complex distribution of vegetation types and tree age structure ranging from seedling to mature. (4) Prescribed fire has been used for wildfire prevention and planting preparation since 1952. (5) The SRS has a complex mosaic landscape consisting of uplands (80%, with 0-40% slope) and wetlands (20%, ranging from swamps, deltas, bays and other periodic flooding areas).

In order to reflect the substantial differences in physical and biogeochemical characteristics of the SRS, the simulation domain was divided into 1241 simulation units. The size of each of the simulation unit was 64 ha. However, the Lower Three Runs Tail (lower right, about 2%) of the land (see Fig. 1) was not included in this simulation domain. Most spatial files for Forest-DNDC input were created using ArcGIS 9.2, including the distributions of soils, vegetation types, tree ages, and landscape and hydrological characteristics. Other input files were created using Excel, including harvesting and prescribed and wildfire data.

Fires were simulated using the annual acreage burned. The annual burned acreage was provided by USFS-SR. However, the exact burn locations were not available. We had to assume that burn locations, except burning for planting site preparation, should be in mature or almost mature forest areas (excluding wetlands), and the vegetation type in the burned areas had to be the same as those given in the burning data. Prescribed fire site preparation was assumed to have occurred in the second year after harvest activities, and the residues left by the harvests were not removed. Accordingly, the annual burned acreage provide by USFS-SR was projected onto the simulation units with vegetation and burn types that were in agreement with the burning data. We also assumed that the C loss to fires was only related to forest floor biomass reduced by the fires. Because Forest-DNDC can simulate forest floor biomass, the coefficient of fuel consumption, which is the ratio of the carbon loss to fire to the fuel loading, is needed for modeling C loss to fires. The ratio was derived from the study of the fuel consumption at SRS conducted by Goodrick et al. (2010).

Table 2. Input parameters for Forest-DNDC.

Parameter	Value (hardwood/pine)
Initial leaf N (%)	2 / 1.3
AmaxA (mol $g^{-1}s^{-1}$)	-46 / 9.3
AmaxB	71.9 / 21.5
Optimum photosynthetic temperature (°C)	24 / 24
Minimum photosynthetic temperature (°C)	4 / 2
Amax fraction	0.76 / 0.76
Growth respiration fraction	0.25 / 2.5
Dark respiration fraction	0.1 / 0.075
Wood maintain respiration fraction	0.07 / 0.07
Root maintain respiration fraction	1 / 1
Light half saturation constant	200 / 200
Respiration Q10	2 / 2
Canopy light attenuation	0.5 / 0.58
Water use efficiency	13.9 / 13.9
DVPD1	0.05 / 0.05
DVPD2	2 / 2
Maximum leaf growth rate (% yr^{-1})	0.9 / 0.35
Maximum wood growth rate	0.8 / 0.9
Leaf start TDD	400 / 900
Wood start TDD	400 / 900
Leaf end TDD	1300 / 1600
Wood end TDD	1300 / 1600
Fraction of foliage N translocation before leave falling down	0.5 / 0.5
Senescence start day	260 / 270
Leaf C/N	23 / 35
Wood C/N	200 / 200
Leaf retention years	1 / 2.25
C reserve fraction	0.75 / 0.75
C fraction of dry matter	0.45 / 0.45
Specific leaf weight (g m^{-2})	100 / 280
Minimum wood/leaf	1.4 / 1.25
Leaf geometry	2 / 1
Maximum N storage (kg N ha^{-1})	200 / 200

Since the harvest locations were unknown, the annual harvest volume provided by USFS-SR was integrated into equivalent harvest acreage based on the harvested species group and corresponding growth rate in the Southeastern USA as reported by Smith et al. (2006). We assumed that the trees harvested were either mature or nearly so. Although there were some thinning operations at SRS and Forest-DNDC is able to simulate thinning practices, data on specific location and volume weren't available to model thinning practices. Thus, we assumed

that all the harvested volume was derived from clear-cutting. If the harvested amount was not enough to be half of the biomass in one simulation cell, the harvest was negligible. The annual harvest acreage was assigned to the simulation units based on the vegetation types and harvesting time obtained from USFS-SR.

2.3.3 *Model Validation*

The model was validated using the forest inventory data from 1951 and 2001, including validation against total biomass and fuel wood mass. These long-term records are good for testing the model performance under various climate and forest management scenarios on a large mosaic landscape consisting of uplands (80%) with 0-40% slope and wetlands (20%) comprised of swamp, Carolina bays and periodic flood areas.

2.4 *Live Cycle Analysis*

The life cycle of wood products was analyzed using the Forest Industry Carbon Assessment Tool (FICAT) developed by NCASI (2009) to estimate C stored in the products in use at 100 year time horizon. We distinguished forest product C as sawtimber and pulp. The life of wood products can be substantially influenced by the type of the product in use (e.g., furniture or fence) and the method of ending their life (e.g., land fill or fuel use); thus, 17 scenarios were developed to assess the carbon life of forest products (Table 3). Eight scenarios (C1-C8) were configured for estimating the C life cycle of sawtimber, which included differences in sawtimber usage. The scenarios C1-C4 were used for assessing the impact of the half life (5, 15, 30 and 50 years) on the C life of the forest product, and assumed that the product was put in a landfill at the end of its life without a fraction used as fuel or recycled. The scenarios C5-C8 were used for estimating the impact of different fractions (20, 40, 70 and 100%) of the product in use consumed as fuel at its life end. We assumed that all sawtimber products were made without preservatives.

For pulpwood, we assumed that it was used to produce uncoated paper (e.g., printing/writing). Nine scenarios (P1-P9) were developed. The scenarios P1-P5 were designed for assessing the impacts of differences in the use of the used paper (landfilled, and used as fuel in different proportions) on C storage, without recycling. The scenarios P6-P9 were developed for estimating the recycling effect, with the assumption that the used paper was land-filled at the end

of use. Generally, an increase in the paper recycle rate should raise C storage in the product due to an increase in the C life of the product. However, the C storage cannot be incremented with an increase in the used paper recycling rate for the model inputs using the FICAT model. Therefore, we manually changed the half life of the pulp wood based on the assumption that the life of the product in use (paper) would be ended when the reusable amount of the product in use was lower than 1% of the raw material.

Table 3. Scenarios for carbon life cycle analyses*.

Scenario	Half life (years)	Landfill (%)	Fuel (%)	Recycle (%)	CH_4 collection rate (%)	Waste rate (%)
C1	5	100	0	0	75	25
C2	15	100	0	0	75	25
C3	30	100	0	0	75	25
C4	50	100	0	0	75	25
C5	30	0	100	0	0	25
C6	30	30	70	0	75	25
C7	30	50	50	0	75	25
C8	30	80	20	0	75	25
P1	2	100	0	0	75	5
P2	2	80	20	0	75	5
P3	2	50	50	0	75	5
P4	2	30	70	0	75	5
P5	2	10	90	0	75	5
P6	3	80	0	20	75	5
P7	5	60	0	40	75	5
P8	7	40	0	60	75	5
P9	12	20	0	80	75	5

*The percentage of landfill and fuel represents how large a fraction of the product in use is landfilled or used as fuel; CH_4 collection rate is the collected fraction of methane generated in the landfills; waste rate is the fraction of the raw product during the manufacturing procedure.

Other settings for the life cycle analysis included: (1) the sum of the C in the product in use and C in the manufacturing waste was equal to the raw solid wood product in forests; (2) C content in all products is 50% of the dry material; (3) landfills were anaerobic; and (4) 75% of methane generated from landfills was collected and burned. The manufacturing waste was totally landfilled due to the limitation of the model. All simulations were to take 100 Mg C of raw forest product per year as the modeling unit such that the total C storage can be easy to estimate

for different wood productions. Therefore, as long as we are given an exact amount of annual forest products harvested, the C storage in various components can be calculated due to a linear relationship between forest production and ultimate C storage based on the model outputs with the same conditions. However, this analysis does not compute greenhouse gas emissions from the procedures of product transportation, manufacturing and purchasing, as well as the emissions from all procedures during the time period from commercial goods in use to landfill operation.

2.5 ***Net Ecosystem Production***

Net ecosystem production (NEP) is a commonly used metric designed to reflect the change in organic matter (e.g., C) accounting for a change in pool sizes and fluxes from the area of consideration. Accordingly, it provides a basis for assessing the change in aggregated organic matter constituents exclusive of gas exchange. NEP was estimated using the equation as described by Lovett et al. (2006):

$$NEP = \Delta C_{org} + E + O_x - I \quad (13)$$

where ΔC_{org} is the change in organic C stored in ecosystem pools; E is the exported organic C; O_x is the part of oxidized organic C; I is the imported organic C. As mentioned above (Sec. 2.1.4), the mineral soil C pool (e.g., excluding forest floor) was assumed to be constant, and therefore did not contribute to NEP.

3. Results

3.1 *Carbon Balance Estimated Using Inventory Data*

3.1.1 Change in Land Use

Land use change on the SRS has been significant (Table 4). Agricultural land that existed in 1951 was converted to forests over the ensuing decades, resulting in an increase in forest land area from 48,903 ha in 1951 to 73,836 ha in 2001; an increase of approximately 40%. The net increase in forest area is approximately 25,000 ha, which is equivalent to 77 % of the total area of agricultural and pasture lands in 1951. The current area of industrial land (7,079 ha) was derived from a combination of both forest and agricultural lands.

Table 4. Land use area (hectare).

Land Use	1951	2001
Forest (inventoried)	48,903.5	72,089.9
Agriculture	32,279.4	0.0
Forest not inventoried	N/A	1,746.4
Developed	N/A	7,079.0
Total	81,182	80,915

3.1.2 Carbon in Biomass

There was a large difference in biomass C between 1951 and 2001 (Table 5). The total C storage in forest in 2001 (5,999 Gg, exclusive of non-inventoried forest) was approximately 11.7 times the amount in 1951 (513 Gg). The increase in C storage and density per unit area were influenced mainly by two factors: conversion of agricultural land to forestland and forest management. In the 50-year period from 1951-2001, the total pine biomass C in 2001 was 23.4 times the amount in 1951 and hardwood biomass C was 7.3 times greater, reflecting the combined influence of land use change from agriculture to pine forest, and forest management for low pine stocking on uplands. The C density at SRS changed substantially from 6.31 Mg ha^{-1} in 1951 to 83.2 in 2001, a change of approximately 1,300 %. The increase in C density also illustrates the impacts of both land use change and forest management. The woodlands of the 1950's were low (8.3 Mg C ha^{-1} on average), reflecting the "woodlot" nature of the parcels that were used for grazing, fire wood, and commercial wood products. However, the reforestation of

agricultural lands induced a larger change; those lands had an average C density of 3.28 Mg C ha^{-1} in 1951.

Table 5. Total carbon (C) in biomass and area by land use class for the 1951 and 2001 inventory periods.

Land Use	1951			2001		
	Area (ha)	Total C (Gg)	Area Density (Mg ha^{-1})	Area (ha)	Total C (Gg)	Area Density (Mg ha^{-1})
Forest						
Pine	27,391.8	155.7	5.68	50,045.3	3,774.4	75.4
Pine-hardwood	-	-	-	4,104.5	355.0	86.5
Upland hardwood	10,300.9	90.7	8.80	15,578.1	1,294.7	83.1
Lowland hardwood	11,210.8	160.2	14.29	2,361.9	574.7	243.3
Agriculture						
Crop	30,984.1	102.9	3.32	-	-	-
Pasture	1,295.2	3.1	2.39	-	-	-
Total	81,182.8	512.6	6.31	72,089.9	5998.8	83.2

There were substantial differences in C content of the forest product components between inventories, and the differences between the cover types were also large, approximately 1:28.7 in pine type and 1:8.6 in hardwoods as contrasted between the inventories in 1951 and 2001 (Table 6). However, the proportion of the biomass C in product classes did not vary much between the inventory periods (Fig. 3). Carbon in pine cover type sawlogs in 2001 was approximately 14% higher than in 1951. There was little change in the hardwood product components between the two inventories.

Table 6. Total above- and below-ground carbon in forest product components by cover type.

	Sawlog (Gg)	Pulp (Gg)	Understory (Gg)
1951			
Forest	287.3	119.3	11.26
Pine	98.4	57.3	5.67
Upland hardwood	61.8	28.8	2.47
Lowland hardwood	127.1	33.1	3.12
2001			
Forest	4447.3	1551.5	17.02
Pine	2823.0	951.4	10.18
Pine-hardwood	326.3	28.8	0.47
Upland hardwood	848.8	445.9	5.44
Lowland hardwood	449.3	125.4	0.93

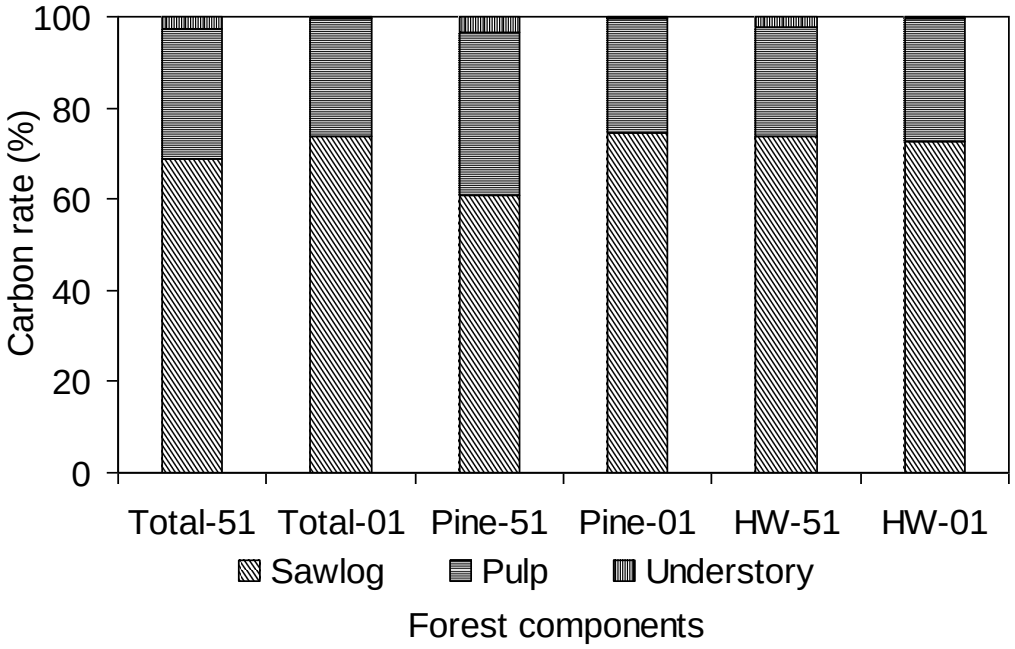

Fig. 3. Proportion of carbon in different forest product components for the aggregated pine and hardwood cover types. Total-51 and Total-01 show the fractions of sawlog, pulp and understoray to total carbon in 1951 and 2001, respectively; similarly, Pine-51 and Pine-01, and HW-51 and HW-01 show the fractions of the sawlog, pulp and understory components in the pine and hardwoods cover types in 1951 and 2001, respectively.

3.1.3 Carbon Removal

Carbon removals from forest lands on the SRS included harvesting, prescribed and wild fires, soil respiration, the riverine C loss brought by water (surface runoff and subsurface drainage) to aquatic systems (Schlesinger and Melack, 1981; Keil et al., 1997; Moran and Sheldon, Jr., 2000; Algesten et al., 2003; Evans et al., 2007), and methane absorption by uplands (Mer and Roger, 2001; Kagotani et al., 2001), and emission from wetlands (Trettin and Jurgensen, 2003). However, data for gas fluxes weren't available; they were only predicted by the biogeochemical model Forest-DNDC (see Section 3.2). The summary of the removals and net changes in C pools are presented in Table 7.

Table 7. Change in carbon pools and flux between 1951- 2001.

	Sequestration (Gg)	Loss (Gg)
Pool		
Biomass[1]	5486.2	-
Soil[1, 2]	315.2	-
Root residue[3]	193.9	
Flux		
Harvested commercial timber		1302.8
Small Round Wood (10 to 24 cm DBH)	-	883.8
Large Round Wood (>24 cm DBH)	-	419.0
Decomposed tops (after harvest)	-	181.1
Decomposed roots (after harvest)	-	257.4
Fire – Total[4]	-	587.9
Prescribed	-	569.5
Wild	-	18.4
Runoff (TOC)[5]	-	105.2
POC	-	26.7
DOC	-	78.5

1 The value did not include carbon storage in non-inventoried forest, appox. 2.4% of the area of the inventoried;
2 Increase in soils C was due to an increase in forest floor; mineral soil was constant;
3 Residual root biomass after harvesting, excluding decomposition (approx. 57%);
4 Carbon loss to fires was only estimated for the 50-year time period from 1952-2001;
5 DOC is dissolved organic carbon; POC is particulate organic carbon; TOC is total organic carbon;

3.1.3.1 Forest Removals - Harvesting

Forest harvest activities at SRS removed approximately 1,303 Gg C during the period from 1955-2000, or about 28.32 Gg C yr^{-1} (Fig. 4). This amount is equal to approximately 18.07 Mg C ha^{-1} removed from the inventoried forest area (72,089 ha). The logging residues (e.g., tree tops and branches) left by harvest activities were approximately 181.1 Gg C, based on the mean tree-top to sawtimber ratio obtained from the 2001 inventory (Parresol, 2004). The root mass from the harvested material was estimated to be 451.3 Gg C in 2001 (Table 7), of which 257.4 Gg C have decomposed over the 1955-2001 period.

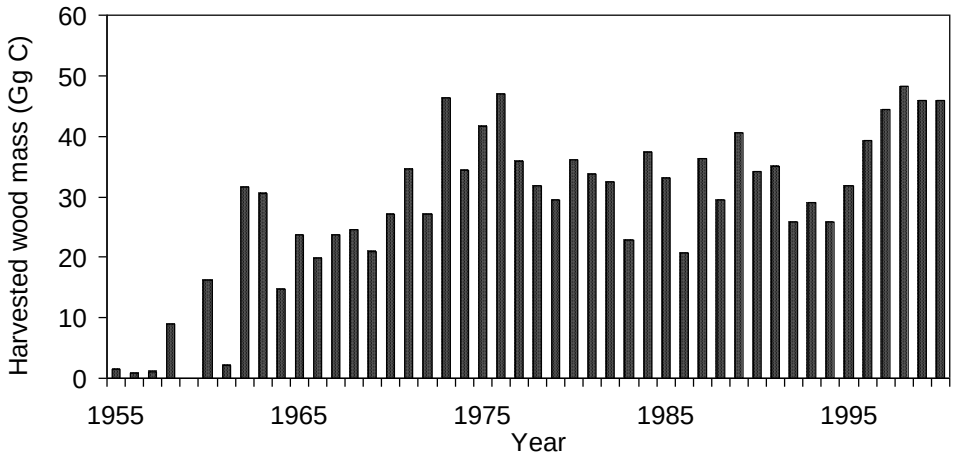

Fig. 4. Harvested solid wood product in the 46-year period.

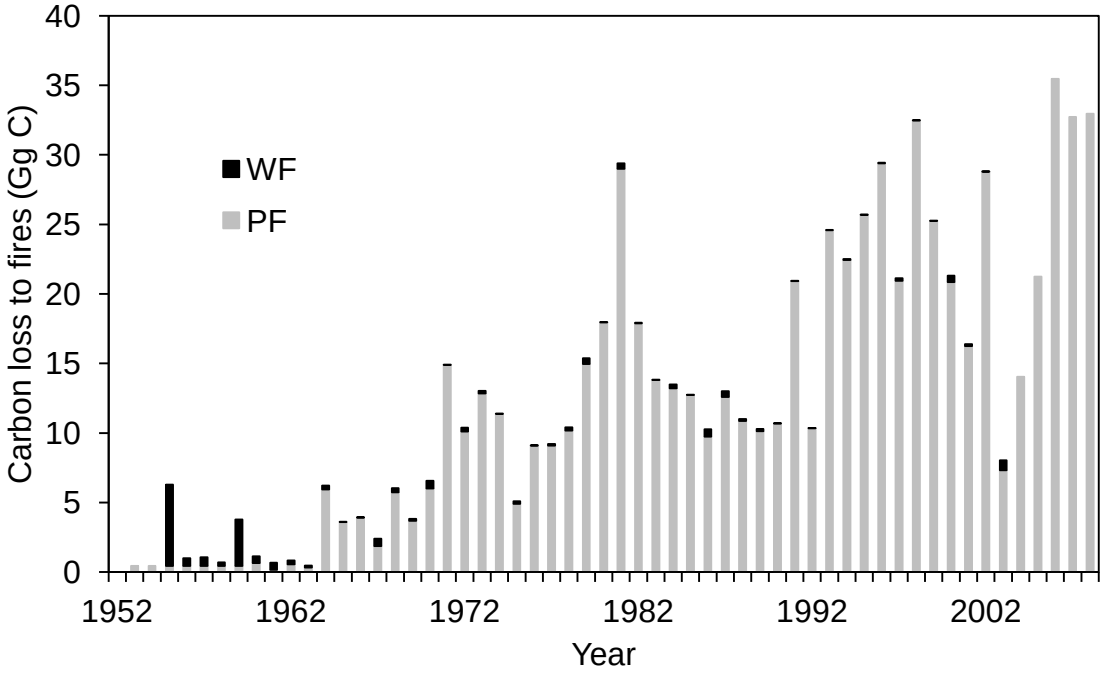

Fig. 5. Carbon loss to prescribed and wild fires in the period from 1952-2007 (PF is prescribed fire; WF is wildfire).

3.1.3.2 *Prescribed and Wild Fires*

Fires consume vegetative fuels and reduce the soil C pool (primarily forest floor C). The estimated C loss to fires was 587.9 Gg C with an average of 12.0 Gg C yr^{-1} during the period from 1952-2001 (Fig. 5). This equates to 569.5 Gg C lost to prescribed fire and 18.4 Gg C to wildfire, based on the mean fuel consumption on the Upper Coastal Plain in South Carolina as

reported by Goodrick et al. (2010). This estimate is necessarily driven by a mean consumption rate, and therefore does not reflect the actual fuel conditions. Accordingly, we consider this estimate conservative.

3.1.3.3 *Carbon Loss to Streams*

The C loss from the SRS through stream flow was much smaller than the losses to fire and harvesting. The average annual TOC loss was approximately 2.1 Gg C, or 105.2 Gg C over the 50-year period (Table 7), in which POC was about 25.4% of the total riverine C loss, and DOC was 74.6%. Riverine C loss at the SRS based on this study (about 2.84 g C $m^{-2}yr^{-1}$) is slightly lower than the mean level of riverine C loss (3.26 g C $m^{-2}yr^{-1}$) from USA's temperate forest watersheds with areas less than 10,000 km^{-2} as reported by Schlesinger and Melack (1981).

3.1.4 Soil Carbon

Carbon storage in soils (to a depth of 1.5 m) at SRS was estimated at 124 Mg ha^{-1} for the 1951 and 2001 inventory using the data from NRCS (Rogers, 1990) (Table 8). While we recognize that land use change may influence soil C content in soils (Post and Know, 2000; Woodbury et al., 2007), because of the data limitations (Sect. 2.2.3), we assumed a constant amount in the mineral soil. The only change that we included was the contribution of the root residue from harvested biomass (194 Gg C). However, the land use data did provide a basis to assess the C change pool associated with the forest floor. The average forest floor C was about 6.0 Mg ha^{-1} in 2001 based on the results reported by Parresol (2004; 2006) (Table 8), 3.6 Mg ha^{-1} greater than the amount on the woodlots in 1951. While the mean of 6 Mg ha^{-1} was on the low end range (3.2-15.2 Mg C ha^{-1}) reported for SRS (Goodrick et al., 2010), it is a robust estimate based on the sample-based inventory. The forest floor mass on the SRS is lower than the regional average of 8.8 Mg C ha^{-1}, which had a range from 0.8-24.8 Mg C ha^{-1} (Smith and Heath, 2002). Over 70% of the forest floor C at SRS was in coarse woody debris (CWD) in 2001 (Parresol, 2004). The lower forest floor C and high rate of CWD are likely related to frequent prescribed fire which function to reduced the litter and duff layers.

Table 8. Soil carbon content on the SRS, excluding industrial areas, in 1951 and 2001*.

	1951		2001	
	Total (Gg)	Mg ha^{-1}	Total (Gg)	Mg ha^{-1}
Forest Floor	117.4	2.4	432.5	6.0
Mineral soil	8939.2	124.0	8939.2	124.0

*Forest floor includes litter and duff; soil organic carbon in 0-1.5 m mineral soil was counted; non-inventoried forest area in 2001 is not included.

3.1.5 Biomass Carbon Sequestration and Net Ecosystem Production

To estimate the total C sequestration on the forest area over the 50 year period on the SRS, we assumed that the C density in the non-inventoried forest in 2001 (1,746.4 ha, approximately 2.4% of inventoried forest area) was the same as the density in the inventoried forest, and we ignored the small difference in total land area over the 50-year period. Accordingly, the total C sequestration in biomass was 6,933.3 Gg C[1], an equivalent to 138.6 Gg C yr^{-1}. The mean annual sequestration rate in biomass for the 1951-2001 period was 1.87 Mg C ha^{-1} yr^{-1}. Harvest removals represented 18% of the total biomass C sequestration, an equivalent to 0.35 Mg C ha^{-1} yr^{-1}. The current (2001) density of C in bole wood on the site is approximately 54.3 Mg C ha^{-1}.

The net ecosystem production (NEP), from the Eq.13, incorporates the change in biomass as well as fluxes from the system[2]. The net increase in C storage (ΔC_{org}) was 122.6 Gg C yr^{-1} (112.4 Gg C yr^{-1} stored in wood biomass and 10.2 Gg C yr^{-1} in soils on average). With respect to fluxes, the I-term was considered as null because there weren't additions or externally derived inputs to the system. The E-term (export) includes TOC export in stream water and harvested wood, averaging 28.1Gg C yr^{-1}. The oxidation term (O_x) was used to represent the oxidation losses due to fire, which averaged 11.7 Gg C yr^{-1}. Therefore, the NEP for the SRS is equal to 162.4 Gg C yr^{-1}, or approximately 2.2 Mg C ha^{-1} yr^{-1}.

[1] Total biomass C sequestration calculated as difference in total C in 1951 (512.6 Gg) and the estimated total for 2001 based on the average C density (83.2 Mg ha^{-1}) across the entire forested area (73,836 ha), plus the harvest removals (1,302.8 Gg).

[2] For purposes of calculating NEP, we utilized the entire forest area (73,986 ha), assuming the average C density in 2001 as previously described.

3.2 Carbon Balance Evaluated Using the Forest-DNDC Model

3.2.1 *Wood Biomass*

The simulated forest biomass C storage on the SRS for the two inventory periods is presented in Fig. 6. The simulated biomass was 8.1 Mg C ha^{-1} for 1951, about 0.2 Mg ha^{-1} less than the inventoried value. The difference maybe an affect of the simulation which used a combination of the a starting forest age based on 2007 stand age information that was available, in conjunction with volume based on the inventory. The model slightly over predicted the biomass for 2001 (90.1 Mg C ha^{-1}), about 1.2% higher than the inventoried value (89.0 Mg C ha^{-1}) based on the Smith et al. (2003) approach, and about 8.9% higher than the inventoried value using the method based on the relationship between volume and weight of commercial woods (Wenger, 1984) (see Section 2.2.2). This difference in simulated versus inventory estimate is likely within the error range produced by the biomass estimation methods. Accordingly, we considered the simulated forest biomass to be in agreement with the inventories.

There was a small systematical error in the modeling of C in fuel biomass (including live fuel trees and standing dead wood). Forest-DNDC slightly under predicted the fuel C for both inventory periods (Fig. 6). The contrast between the simulation estimate and inventoried value was 2.2 vs. 2.4 Mg C ha^{-1} for 1951, and 12.2 vs. 12.9 Mg C ha^{-1} for 2001, approximately 8.3 and 5.4% lower than the measured values, respectively. The overall comparison of the simulated forest biomass to the inventoried values for 1951 and 2001 showed that the watershed scale Forest-DNDC model was effective at predicting forest growing stock on the SRS.

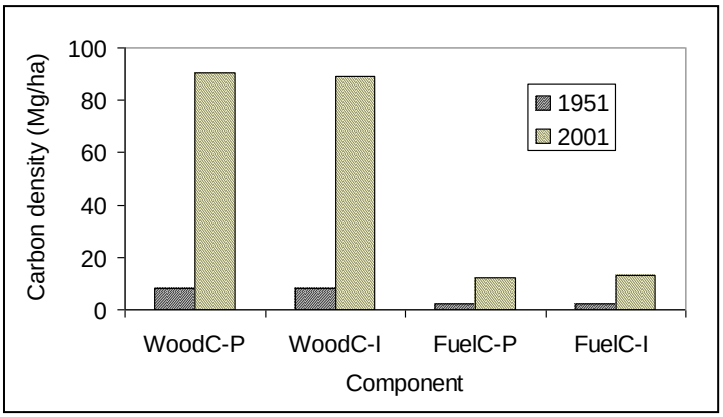

Fig. 6. Simulated (P) and inventoried (I) biomass carbon storage (Mg C ha^{-1}) in the forest product classes on the SRS. [Wood C denotes total carbon in tree biomass, and Fuel C denotes carbon in live and standing dead fuel wood (< 12 cm DBH)].

3.2.2 *Harvests*

The comparison of the simulated annual harvested C and the actual harvested C during the period from 1955-2000 is presented in Fig. 7. The result showed that the model captured the harvest activities well. The simulated total harvested solid wood product (1,300.3 Gg C) was approximately to the actual harvested amount (1,302.8 Gg C). However, there were some small differences in annual harvested amount for some years. These errors were mainly resulted from the large the simulation unit. This error could be reduced by using a smaller cell size, but a longer run time would be needed.

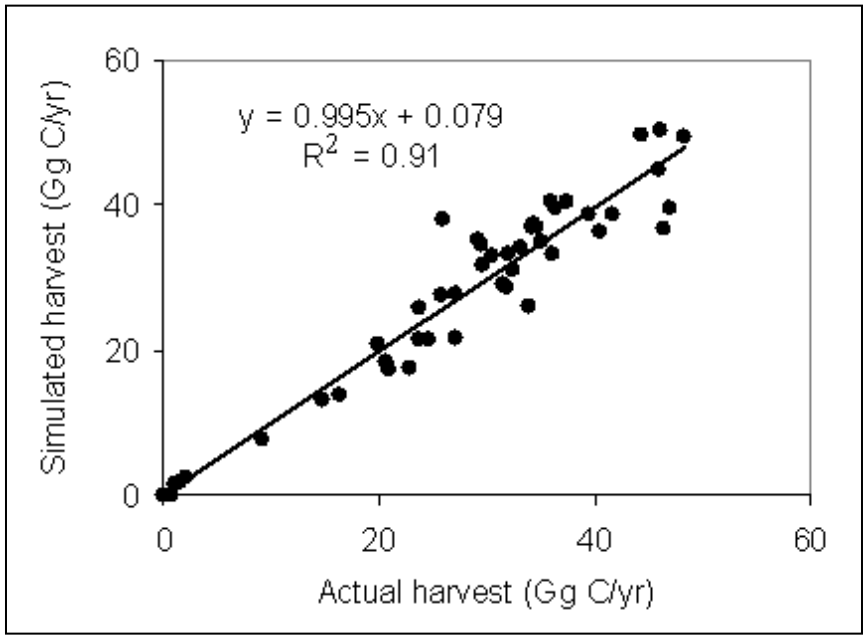

Fig. 7. Simulated annual harvest of wood product C at SRS vs. actual annual harvest across the 46-year period 1995-2000.

Although there were small differences between the harvested wood mass from this simulation and the actual harvest, the model performance efficiency ($E \leq 1$) (Nash and Sutcliffe, 1970) was very high ($E=0.91$, $n=46$), and the simulated total harvested wood biomass (1300.3 Gg C) was only 0.2% lower than the actual harvested amount (1302.8). The slope and intercept of the regression model between actually harvested wood product and the simulated value were 0.995 and 0.079, respectively (Fig. 7). These results indicate that Forest-DNDC performed well for evaluating the long-term changes in C stocks on the SRS.

3.2.3 *Carbon Loss to Fire*

Carbon loss to prescribed and wild fire was simulated based on the annual burn area and the average fuel consumption coefficient derived from the study of Goodrick et al. (2010) for SRS (Fig. 8). The result showed a large amount of C loss to the fires. The simulated C loss to fires (636.0 Gg C in the 50-year period from 1952-2001) was about 8% higher than the estimated loss (587.9 in the same period) using average fuel consumption on the Upper Coastal Plain in South Carolina (Goodrick et al., 2010). Nonetheless, the trend in C loss to fires from this simulation was in basic agreement with the estimation with R^2=0.35 (P<0.01). The difference in C loss to the fires between this simulation and the estimation is principally influenced by the prescribed fire for site preparation after harvest activities. This is because the C loss to fires estimated using average fuel consumption and it did not explicitly consider the fuel loading left during harvesting activities. In contrast, this simulation included the site preparation fires explicitly resulting in higher fuel losses (Fig. 8).

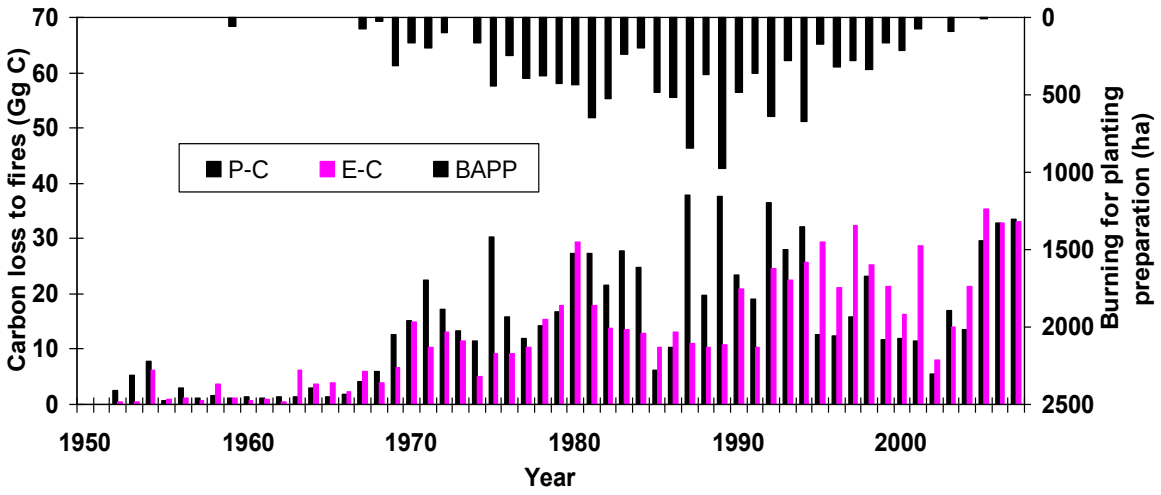

Fig. 8. Total carbon loss to prescribed and wild fires (E-C is the estimated carbon loss to fires using average fuel consumption on the Upper Coastal Plain in South Carolina (Goodrick et al., 2010); P-C is the predicted carbon loss to fires by Forest-DNDC; BAPP is the site preparation burned area (ha).

3.2.4 *Temporal and Spatial Soil CO_2 and Methane Fluxes*

There were temporal differences in simulated soil CO_2 flux at SRS during the study period (Fig. 9). The annual flux ranged from 2.37 to 3.66 Mg C ha^{-1} yr^{1} with an average of 2.84 Mg C (soil C

loss to fires excluded). The inter-annual variation in soil CO_2 efflux was related to the variation in precipitation. Lower precipitation produced a higher soil CO_2 flux due to the reduction in area of soils were saturated near the surface (Pietsch et al., 2003; Dai et al., 2011). For instance, high soil CO_2 flux occurred in 1999-2000 because of a low precipitation period from the middle of May of 1998 to 2001 with only 980 mm average annual precipitation.

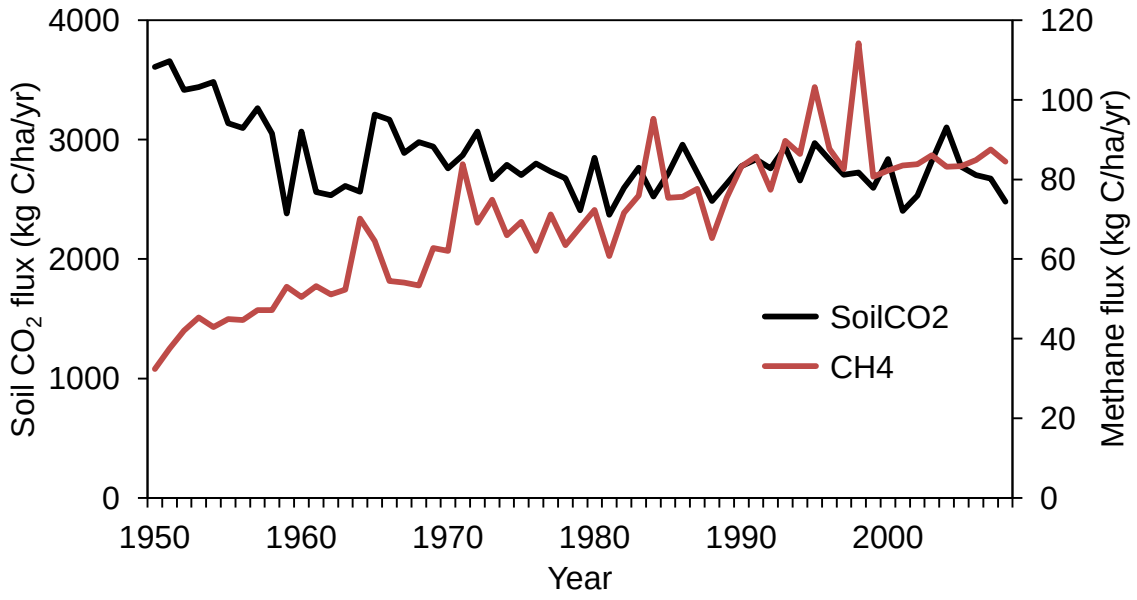

Fig. 9. Simulated methane (CH_4) and soil CO_2 fluxes.

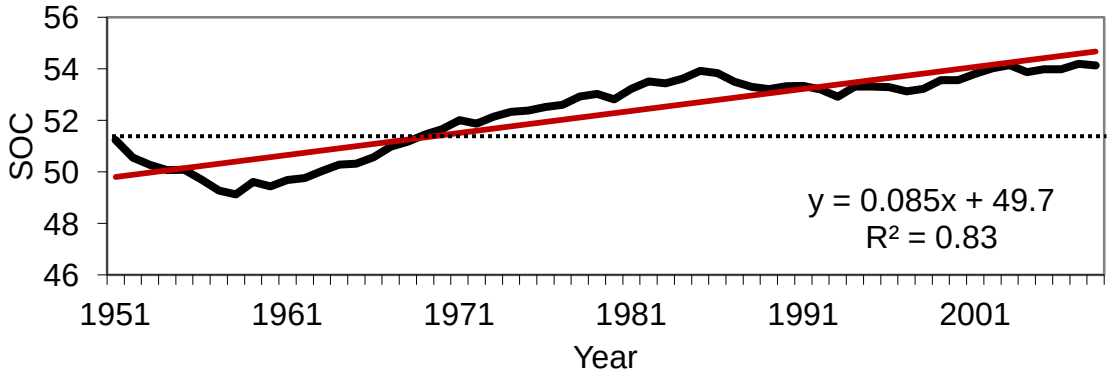

Fig. 10. Simulated soil organic carbon (SOC, Mg C ha^{-1}) at 50 cm below the mineral surface.

The spatial difference in soil CO_2 flux at SRS was large and ranged from 0.76-6.98 Mg C ha^{-1} yr^{-1} during the period from 1950-2008. Both the maximum and minimum soil CO_2 fluxes occurred in wetlands. The minimum fluxes occurred at swamps where soils are under an anaerobic condition for a long period. High fluxes were from wetlands along river/stream

drainages because of the wide fluctuations in water table associated with changes in precipitation. In these areas, there was high soil CO_2 release during low precipitation periods. High soil CO_2 efflux also occurred in shallow Carolina bays that can dry out due to droughts.

The temporal changes in CH_4 flux were inversely related to soil CO_2 (Fig. 9). The wetter the year, the more methane was produced and emitted from wetlands, but the less soil CO_2 released from wetlands. Methane flux occurred primarily from the swamps. The maximum flux was 1.73 Mg C ha^{-1} yr^{-1} from a swamp. The spatial average flux was 25.6 kg C ha^{-1} yr^{-1} for the whole SRS, however it was 357.8 kg C ha^{-1} yr^{-1} from the wetland areas. The upland areas are a CH_4 sink, but the difference in the CH_4 sink in space was large and ranged from 0.1-10 kg C ha^{-1} yr^{-1}. The overall median flux of CH_4 on the SRS was -0.1 kg C ha^{-1} yr^{-1} due to uplands occupying 80% of the land area. Therefore, the spatial distribution of the methane flux at SRS was substantially skewed.

3.2.5 *Impacts of Harvesting and Fires on Net Ecosystem Exchange*

The average simulated net ecosystem exchange (NEE) at SRS was -1.85 Mg C ha^{-1} yr^{-1} during the period from 1950 to 2001. This value was approximate to the estimated average C sequestration to wood biomass (1.72 Mg C ha^{-1} yr^{-1}) from 1951 to 2001. These values indicated that the C is mainly sequestrated to wood biomass in this managed forest, and only a small amount to the forest floor. However, the NEE fluctuated widely during the period from 1950-2008 (Fig. 11) and ranged from -5.07 to 1.15 Mg C ha^{-1} yr^{-1}. The inter-annual variation in NEE was likely related to changes in precipitation. However, low NEE (high C sequestration rate) occurred during the period from the middle of the 1950's to the early 1960's due to the agricultural land being converted to forestland (>2800 ha yr^{-1}) (Blake, 2005), and little harvesting during in this period.

Fires had a small influence on annual average NEE (Fig. 11). Although the impact of fires on NEE in the burned area might be large, the simulated average impact of fires on the annual average NEE at SRS was less than 220 kg C ha^{-1} yr^{-1} during the 56-year period from 1952-2007, based on the simulated C loss to fires. Annual burning had a low impact on NEE for a couple of reasons. First, the annual burned area is only a small part of the forestland (about 4.4%) in spite of an average of over 3000 ha of forestland burned by prescribed and wild fires every year since 1952 Second, the impact of fires on NEE is highly dependent on fuel loading. During periods of

extensive harvesting, fires in the resultant logging residues can substantially increase NEE on site.

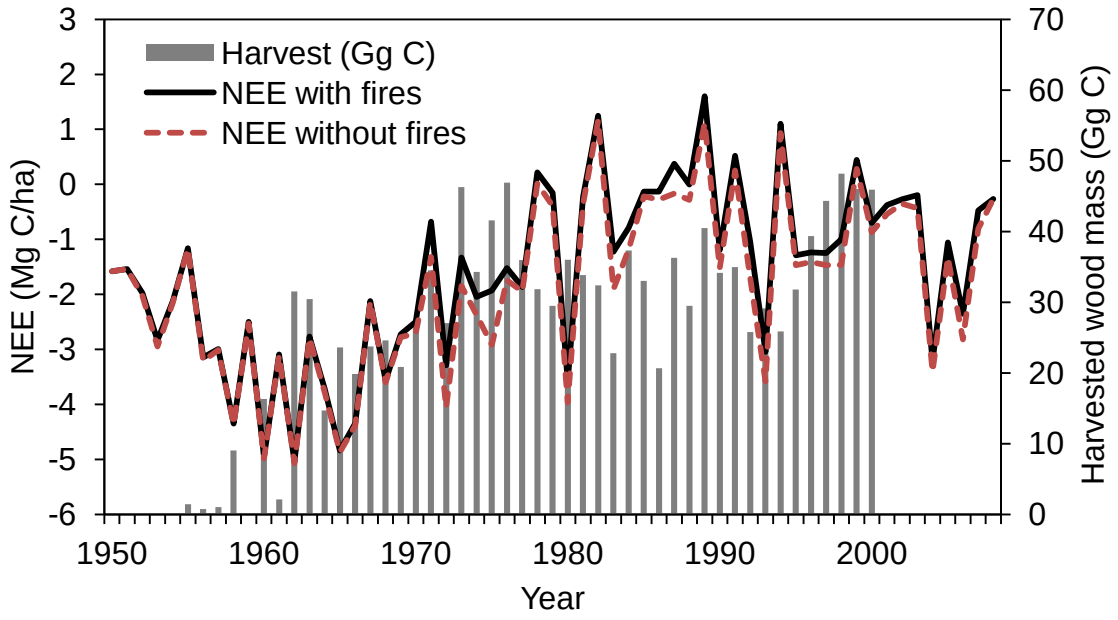

Fig. 11. Annual NEE (Net Ecosystem Exchange) at SRS and impacts of harvest and fires on NEE

NEE was influenced by wood product harvests. The annual average NEE increased linearly with an increase in the logarithmic scale of annual harvested solid wood (R^2=0.24, n=46, P<0.01). The NEE increase with respect to harvest activities resulted from increased CO_2 emissions associated with the harvests and prescribed fire. Principally, however, the increase was the result of the decomposition of the residues left in the fields during the harvests as less than 10% of harvested fields were burned by prescribed fires for planting site preparation.

3.3 SRS Soil C Data

Despite the constraints on utilizing available reports from the SRS that contain soil C data (Odum, 1960; McKee et al., 1983; Odum et al., 1984; Dixon et al., 1997; Looney et al., 1990; Smith, 2000; Sanchez et al., 2003) for the site-wide assessment C pools, an assessment of these data provides a useful basis for comparison to the values used in the inventory assessment (Sec. 3.1.4), as well as informed basis for contrasting the C content in upland and wetland soils on the SRS.

Two detailed studies soil C content data and information about location or soil taxa for uplands (Looney et al., 1990) and wetlands (Dixon et al., 1997) on the SRS. Since those studies did not measure soil bulk density, we utilized published values from the NRCS; in that manner we could contrast soil C estimates that incorporate data from on-site samples and estimates based entirely on the NRCS data (Rogers, 1990). The soil C content of six upland soil taxa on the SRS estimated using NRCS data was greater than the amount calculated using site-specific C concentration data (57.5 vs. 33.5 Mg C ha^{-1}, Table 9). That difference is a reflection of the C concentration data since the bulk density is the same. Interesting, the bias of the NRCS data being greater than the on-site data is not consistent among soil taxa, some estimates for taxa using the NRCS data were lower than the estimate incorporating on-site data. The mean C content in these selected taxa is greater than the mean for all upland soils on the SRS. That finding illustrates the importance of ensuring a balance representation when conducting a large-scale assessment; if the mean from those six taxa were used to represent all upland soils on the site, the estimate would be too large. The bias associated selected taxa is greater than the bias reflecting the weighted distribution of the upland soils across the site (Table 9). The 5 soil series reported by Looney et al., (1990) reflect 23% of upland soil series on the site.

The on-site study of wetland soils by Dixon et al. (1997) incorporated all of the wetland soil taxa, sampling and reporting the soil C data by functional Groups. Again, the study did not include a measure of bulk density, so values were obtained from the NRCS database. Dixon et al. (1997) reported that data based the Group number and sample location (latitude and longitude). We used the latitude and longitude to assess the accuracy of obtaining the NRCS data based solely on location, as contrasted with determining that the location was within a hydric soil map unit within the site (Rogers, 1990). Estimates of soil C content based on on-site C concentration data and bulk density obtained from reported and adjusted locations, to ensure correspondence within a wetland are summarized in Table 10. The reported locations did not have sufficient accuracy to ensure that the sampling points occurred within a wetland; accordingly, if only the reported locations were used as opposed to adjusting the location to ensure occurrence within a wetland, there is a large underestimation (354 vs. 557 Mg C ha^{-1}). In contrast to the upland study, the Dixon study incorporated all the wetlands soils, and the corresponding estimates using the on-site data are very close to those obtained solely with the NRCS database (557 vs. 577 Mg C ha^{-1}). This finding is important, because it further

substantiates the use of the NRCS database for estimating soil C content on the SRS. However, the Dixon study demonstrates the importance of having accurate locations when needing to rely on other information resources to develop an integrated database for assessment purposes. Utilizing the reported sample locations induced large errors, when the locations weren't adjusted to be within a wetland map unit.

Table 9. Comparison of estimates of upland soil C for selected taxa based on data from the SRS (Looney et al., 1990) and the NRCS data base (Rogers, 1990). Estimates are provided for individual soil taxa, for the mineral soil to a depth of 150 cm.

	SRS Data[1]			NRCS data[2]		
Soil Series	Mean	Min	Max	Mean	Min	Max
	---------- Mg C ha^{-1} ----------					
Blanton	47.61	43.00	52.22	77.23	69.43	85.02
Fuquay	36.61	35.14	38.08	45.27	43.22	47.32
Lakeland	44.27	41.67	46.87	84.38	75.94	92.81
Orangeburg	40.78	38.76	42.81	36.50	34.67	38.34
Udorthent	15.79	13.92	17.67	55.31	48.75	61.88
Vaucluse	54.18	49.40	60.48	35.04	32.34	37.74
Mean	33.48	31.05	36.06	57.49	52.40	62.59
median	28.90	27.03	30.16	55.31	48.75	61.88
Mean from NRCS data for all upland soils with area weights[3]				40.13	38.40	41.84
Mean from NRCS data for all upland soils without area weights[4]				46.78	43.97	45.98

1 - SRS estimates calculated using measured soil C concentration from an on-site study (Looney et al., 1990) in combination with the mean soil bulk density obtained from NRCS (Rogers, 1990); the Min and Max estimates reflect the minimum and maximum soil bulk density obtained from NRCS, respectively.
2 - NRCS estimates are calculated using concentration and bulk density data for the soil taxa, obtained from the NRCS database (Rogers, 1990). The Min and Max reflect the minimum and maximum soil bulk density obtained from NRCS, respectively.
3 - Soil C content of all upland soils on the SRS weighted by total area.
4 – Soil C content of all upland soil taxa on the SRS.

Table 10. Estimates of wetland soil C (Mg ha^{-1}) for soil groups on the SRS (Dixon et al., 1997) using a combination of on-site and NRCS data (Rogers, 1990), in combination with two approaches for determining the basis for accessing NRCS database information. 'GIS' refers to NRCS data extracted based on the reported latitude and longitude of the sample location. 'Adjusted Location' reflects adjustment to the nearest hydric soil map unit if the reported location occurred in an upland area*.

	Site study[1]				NRCS data[2]			
Group[3]	GIS		Adjusted Loc.		GIS		Adjusted Loc.	
		σ		σ		σ		σ
1	728.96	462.82	265.33	416.80	87.68	1131.33	2213.80	890.96
2	812.68	340.08	812.68	333.86	540.39	257.89	540.39	193.36
3	464.36	203.09	447.17	196.22	46.00	221.02	461.65	127.77
4	703.37	146.99	659.14	132.92	42.28	11.01	69.56	7.66
5	776.64	397.94	689.40	397.75	51.55	12.40	58.77	3.27
mean	624.28	345.62	577.43	321.26	354.76	650.41	557.55	757.28

1 - Soil C estimated using site specific study's data (Dixon et al., 1997) with the bulk density from NRCS and soil types determined by GIS and manual verification ; calculated to a depth of 200 cm.
2 - Soil C estimated using NRCS data, including bulk density and carbon content, with soil types determined by reported and adjusted locations; calculated to a depth of 200 cm.
3 – Group is the soil grouping given by Dixon et al. (1997); Group 1 was small stream floodplain soils with high organic matter content; Group 2 was small stream floodplain soils with intergrade organic matter content; Group 3 was small stream floodplain mineral soils; Group 4 was soils in Bays and depressions; Group 5 was lager river floodplain soils;

3.4 *Forest Product Carbon Life Analysis*

The results of the carbon life cycle analysis are presented in Table 11. The results showed that the C fate in timber is correlated to the duration of the half life of the commercial product in use ($0.02<P<0.05$). Although the C stored as a product can significantly increase with an increase in the half life (an approximate increase of 2.1% with an increase of 10 years in the half life) the incremental coefficient of total C storage is small, about <0.5% if the half life is increased by10 years; this is because C storage in landfills can decrease by over 1.6% with an increase of 10 years in the half life. However, if the product was ultimately used as fuel, the C storage is largely diminished, a decrease of 2.6% with an increase by 10% of the product as fuel at the end of product use. Therefore, the C storage in the product made from sawtimber is highly dependent on the end-of-product use and on its half life.

Table 11. Annual carbon storage rate (%) in different components under different scenarios*

Scenario	C SPU#	C in landfills	C in manuf. Waste	Total stored C
C1	0.00	28.87	7.22	36.09
C2	0.37	28.59	7.22	36.18
C3	3.72	26.01	7.22	36.95
C4	9.38	21.66	7.22	38.25
C5	3.72	0.00	7.22	10.94
C6	3.72	7.80	7.22	18.74
C7	3.72	13.01	7.22	23.95
C8	3.72	20.81	7.22	31.75
P1	0.00	5.70	0.00	5.70
P2	0.00	4.56	0.00	4.56
P3	0.00	2.85	0.00	2.85
P4	0.00	1.71	0.00	1.71
P5	0.00	0.57	0.00	0.57
P6	0.00	4.56	0.00	4.56
P7	0.00	3.42	0.00	3.42
P8	0.00	2.28	0.00	2.28
P9	0.15	1.14	0.00	1.28

* All values are equal to Mg C storage per 100 Mg C of raw wood product;#: C SPU is the carbon stored in the product in use

The pulp wood life cycle is largely a function of the used paper use. The results from scenarios P1 to P5 showed that an increase in used paper as fuel decreased the pulp wood C storage, but the storage rate can be increased if the landfill rate of the used paper is increased. However, it was surprising that the increase in C storage in the product in use was very small as the recycling rate increased. The C storage in the product only increased by 0.54% as the reuse rate approached 80%.

4. Discussion

4.1 *Effect of Land Use Change and Forest Management on Carbon Sequestration at SRS*

The changes in land use on the SRS have influenced C sequestration. The effects of reforestation of agricultural lands have been documented at the field-scale, typically showing a net increase in C storage (Johnson et al., 2002; Dushku et al., 2007, Houghton and Goodale, 2004). This is the first study documenting the long-term (e.g., 50 years) change in C storage across a broad landscape. The increase in C storage on the original agricultural lands on SRS

that are now forested is approximately 80 Mg C ha^{-1}, or 1.6 Mg ha^{-1} yr^{-1}. However, it should be recognized that the change in C storage does not accumulate at a constant rate over time; as forest stands mature the rate of net accumulation declines relative to the early stages of stand development.

Active forest management is also an important factor contributing to the site-wide increase in C storage on the SRS. As farm woodlots, most the forest lands in 1951 carried low stocking rates and were likely grazed resulting in low understory and forest floor mass. The C carried in forest vegetation on the SRS increased from 8.3 Mg ha^{-1} in 1951 to 83.2 Mg ha^{-1} in 2001, yielding a net increment of approximately 3,662.9 Gg C. The change in forest floor C was also significant, increasing by approximately 3.6 Mg ha^{-1}. The forest floor mass represents a standing average across the site, recognizing that sites recently burned will have lower amounts, and sites that are not burned may carry higher amounts. These results, integrating the effects of management over a 50 year period, demonstrate that active management can substantially enhance C storage relative to unmanaged rural landscapes. While other studies have reported an increase in terrestrial C storage as a result of afforestation or intensive management (Nilsson and Schopfhauser, 1995; Masera et al., 2003; Niu and Duiker, 2005; Woodbury et al., 2007), this the first study with the capacity to document the effect across a complex forested landscape which contains a wide variety of forest types.

4.2 *Influence of Harvests*

Harvesting not only changes the distribution of live biomass in the forest, but it also impacts the forest floor and soil C due to logging residues (e.g., tree tops) and roots systems (Fig. 12). Those residual materials can influence SOC (Johnson, 1992; Yanai et al., 2003; Butnor et al., 2006), and they can also increase soil CO_2 flux due to an increase in organic matter decomposition from the harvest-residual inputs to the forest floor (Johnson, 1992; Yanai et al., 2003). Fig. 12 shows that the accumulated root mass left by harvesting in 1955-2000 was approximately 588 Gg C. However, the residual root mass was approximately 193 Gg C in 2000 due to decomposition.

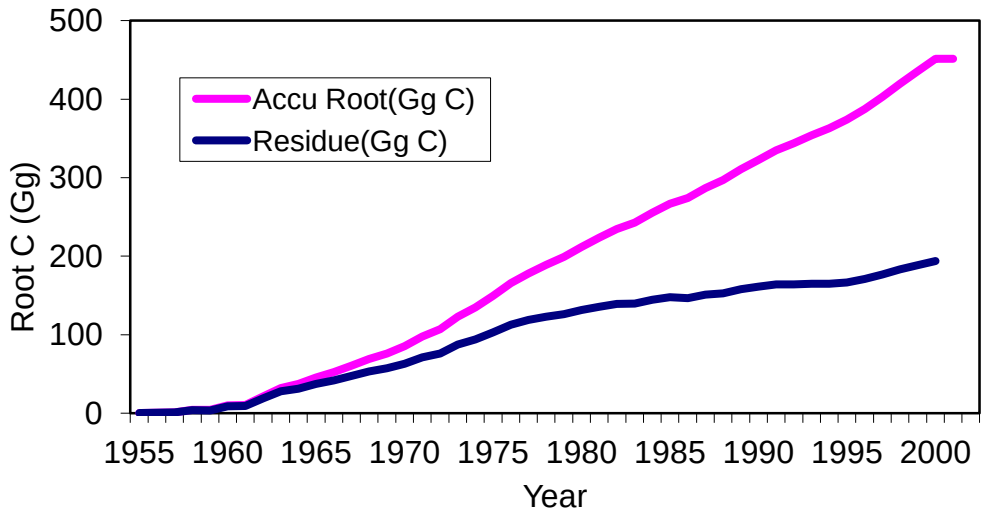

Fig. 12. Cumulative root biomass (C Gg) due to harvesting, and residual biomass accounting for decomposition (1955-2000).

4.3 *Net Ecosystem Production*

A comparison of net ecosystem production (NEP) at SRS to other studies is presented in Fig. 13. The NEP at SRS reflects a level (2.18 Mg C ha^{-1} yr^{-1}) that is well within the range reported across the boreal to tropical climatic zones. The differences among studies are largely related to climate and site conditions. But the period of measurement is also a factor. The other study reported for the subtropical zone (Yu et al. 2008), documents productivity over a four year period (2001-2005), in contrast to the 50 year average represented by this study. Species differences are also an important consideration when assessing NEP among sites. Accordingly, these results demonstrate that the NEP of the SRS is maintaining a relatively high rate of production, as determined by an average generated across a broad landscape over a long period.

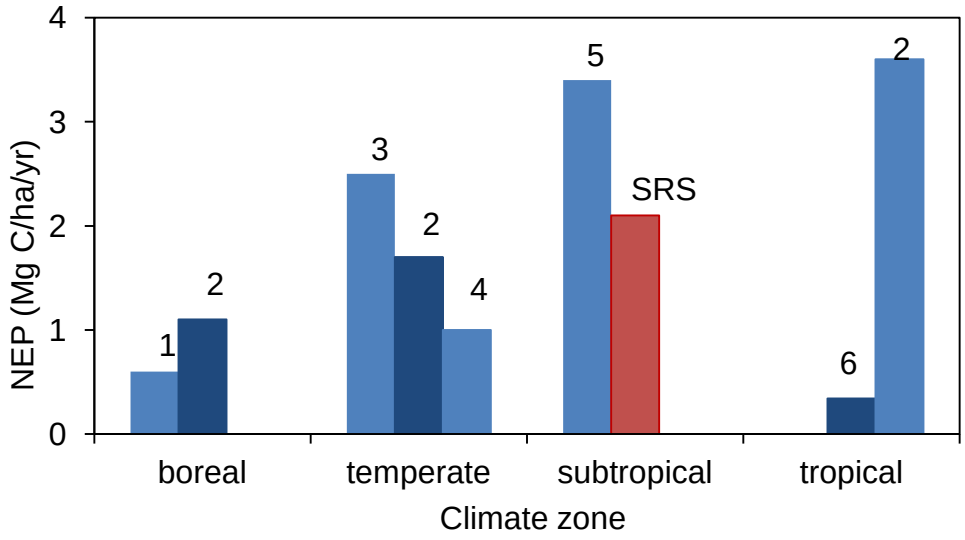

Fig. 13. Comparison of NEP (Net Ecosystem Production) at SRS to other studies. The number above the bar references the study: 1: Li et al. (2003) and Amiro et al., 2004; 2:Pregitzer and Euskirchen, 2004; 3: Campbell et al., 2004; 4: Aber et al., 1995; 5: Yu et al., 2008; 6: Sierra et al., 2007.

4.4 *Impact of the Half Life of Forest Product on Carbon Storage*

Assessing the fate of C stored in wood products is dependent on the type of product and the estimated half life. Accurate estimates necessitate specific linkages from the harvested material into a product, an exercise that wasn't feasible given the resolution of the available data. Instead, our purpose was to illustrate the effect of considering forest products on the assessment of the C balance on a large site when a long time period (e.g., 50 years) was considered. We assumed that (1) the product was obtained from a clear-cut at the end of 2001, (2) the half life of the product in use made from the sawlog was 50 years, (3) the pulp was used to produce printing paper without recycling, (4) the life of all products ended at landfills, and (5) 75% of methane generated from landfills was burned. The combined effect yielded 2,943.3 Gg C solid wood products from sawlogs and 1026.8 Gg C in pulp. Tree crown materials left by the harvest would be approximately 756.2 Gg C, and roots would yield about 927.3 Gg C. After 100 years, the total C storage would be about 1,125.8 Gg C for sawlogs and 58.5 Gg C for pulp. This means that 3,541.9 Gg C (exclusive of tree crown and roots) would be converted to CO_2 and emitted into the atmosphere after the life of the products, assuming a half life of 50 years. The root mass left in soils would exponentially decrease. Thus, the residual root C would be about 64.2 Gg C

in the 50th year since the harvest and about 863.2 Gg C would decompose. If the tree crown material is left in the field, it would decompose in a short period (<10 years).

4.5 *Assessment of Soil Carbon*

The soil C content data available from publications reporting on-site (e.g., SRS) measurements (Odum, 1960; McKee et al., 1983; Odum et al., 1984; Dixon et al., 1997; Looney et al., 1990; Smith, 2000; Sanchez et al., 2003) were within the range of values contained for the soil units in the NRCS database. Similarly, studies specifically designed to assess soil C on uplands and wetlands within the SRS (Dixon et al., 1997; Looney et al., 1990) reported data that fell within the range contained in the NRCS database. Accordingly, the use of the NRCS database as the basis was reasonable, since it was the only data source representative of the entire site.

The available soil characterization data consisted of a range for each of the soil units. Accordingly, the algebraic mean of soil organic C content (SOC) for each soil type was employed to estimate soil organic C storage for the soil types (Buringh, 1984; Batjes, 1996; Powers et al., 2004). This approach has inherent issues, including the potential to overestimate or underestimate the mean for the soil type because the distribution of C content in a soil type may be heterogeneous or skewed (Gower et al., 1997; Franzluebbers et al., 1999; Jobbagy and Jackson, 2000; Wang et al., 2003). However, given the large spatial scale of the assessment, there was not another basis that could be used consistently across the site for each of the soil types.

Our assessment assumed that there has not been any change in the soil C pool over the 50 year period. This assumption is recognized to be erroneous, since cultivation is known to reduce soil C pools, and the reforestation activities should have increased the soil C content on the agricultural sites (Post and Kwon, 2000; Johnson et al., 2002; Niu and Duiker, 2006). Unfortunately, there wasn't a substantive basis to estimate soil pools in the 1950's, the land inventory did not include a soil inventory or assessment, and there is little basis in the literature to suggest how this site may have changed over time. Accordingly, we chose to assume that there was no change in the soil C pool, because we could not substantiate an alternative scenario. It is reasonable to assume that given the long agricultural legacy of the SRS lands before 1951, that there has been a gain in soil C since forest management of the site commenced in 1951.

Unfortunately, the lack of a decent starting basis and the lack of a contemporary inventory preclude estimation. As a result, the overall change in C pools for the site for the 50 year period is quite likely an underestimate.

4.5.1 *Assessment of Soil Carbon Data*

There are 50 soil types comprising 30 soil series on SRS; the soils range from sandy in sloping uplands to organics in the flat bays and swamps. Just the inherent landscape variability suggests the complexity of estimating the distribution of soil C. Unlike many sites, the SRS contains site specific data. While we deemed that information as too limited to serve as a basis for the assessment of the C pools across the 50 year inventory period, it does provide useful information for assessing specific soil types, and for planning future work that may attempt to provide better estimates of the soil C pools.

The NRCS national database is intended to provide a broad basis for assessing soil resources. It reflects the compilation of data throughout the range of the specific soil taxa. In contrast, the site-specific studies on the SRS were designed to provide information for specific objectives, in this case, an assessment of pollutants from the industrial activities. The difference in SOC estimates using the two data sources reflects differences in the source data, and demonstrates the need for complimentary data. For example, C concentration data must be coupled with a measure of soil bulk density to calculate a C pool; hence if the Db measure isn't available an assumed value must be substituted. Having a complete spatial coverage is also important; the NRCS database provides estimates for each soil type, while the SRS study on upland soils only addressed 5 of the soil series, and area representing approximately 57% of the upland area. Accordingly, those data do not provide a balanced representation of the upland soils on the site. There is a difference in average C storage in wetland soils estimated using the 50 samples from the site specific study and data from NRCS although the 50 samples covered all wetland soil types. Accordingly, the difference in average C storage in wetland soils estimated using different data sources may be principally related to the sampling methods and sites. For example, the unified thickness of soil layers for most soil profiles were employed by Dixon et al. (1997), but NRCS utilizes natural soil layer thickness.

The second important factor affecting the estimate of soil C storage is the soil bulk density. The Db used to estimate SOC for the upland and wetland samples was from the NRCS database

because Db was not measured. The SOC estimated using maximum bulk density was over 27% higher than minimum Db for upland and wetland soils at SRS (Figs. 14 and 15). This result illustrates importance of soil bulk density for estimating SOC.

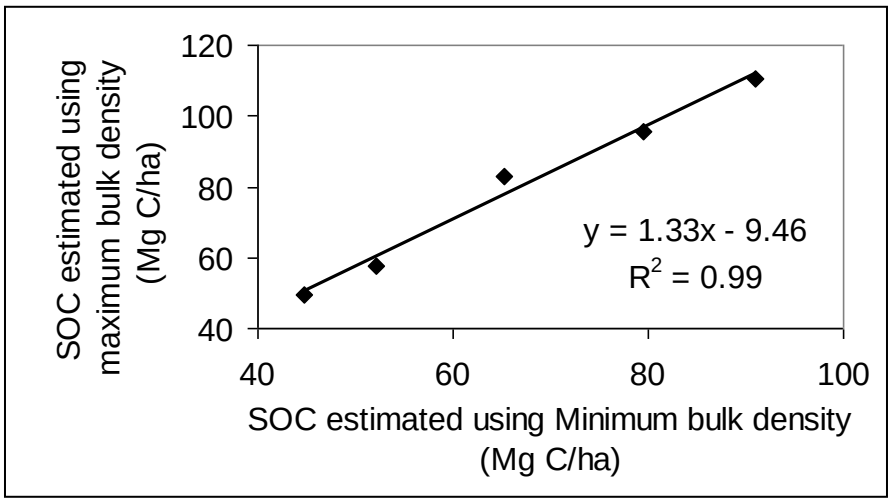

Fig. 14. Soil organic carbon (SOC) estimated for upland soils using different bulk densities. (SOC can be over or under estimated if there is not an accurate bulk density for estimating SOC).

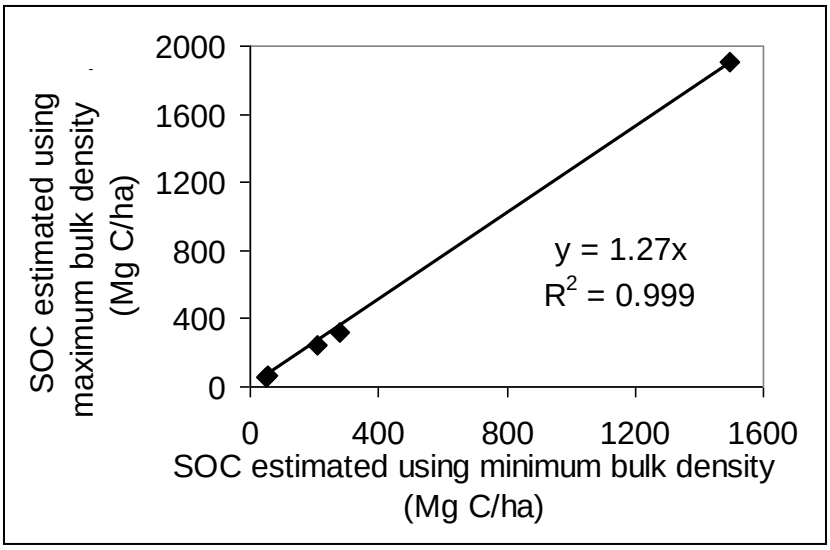

Fig. 15. Soil organic carbon (SOC) estimated for wetland soils using different bulk densities.

5. Conclusions and Perspectives

Determining the outcome of individual actions across a complex landscape over a long period (e.g., 50 years) is the "holy grail" for assessing sustainability of resource management objectives or resource use. Typically, research studies provide a short term perspective (e.g., 3-5 years) on the system performance or response to a specific treatment, and that is usually only for a given site. In contrast, the unique situation of the SRS lands provided the basis for an empirically based assessment of the cumulative effects of land use and management over a 50 year period. Assessing the change in condition over a well-documented 50 year period across a landscape effectively integrates the cumulative effect of land use and management prescriptions both spatially and temporally. Fortunately, utilizing forest inventory data to provide a basis for assessing C stocks is well established and straightforward. Accordingly, this work is unique in its ability to assess the change in C stock at spatial and temporal scales that typically aren't feasible without the aid of simulation exercises.

The unique and important perspectives from this study are (1) the long-term effect of forest management on the C balance of the landscape, and (2) the complete accounting of C fluxes from the landscape across a 50 year period. While a net gain in ecosystem C storage is expected with reforestation and active forest management, the net gain of 80.5Mg C ha^{-1} across the site demonstrates the effect at a spatial scale that is relevant to regional assessments (> 50, 000 ha) and a time scale that reflects the sustainability of the findings. Incorporation of the fluxes associated with forest management (e.g., prescribed fire, harvesting) and forest ecosystem processes (e.g., organic matter decomposition) added important perspective because they were based on actual operations across a multitude of stands and periods. Consideration of the fluxes added effectively 1,600 kg ha^{-1} yr^{-1} C to the balance sheet. Given the national and international interest in reforestation of agricultural landscapes as a means to enhance terrestrial C sequestration, the change in the C balance on the SRS is a testament to the viability of the intent.

The annualized change in C stocks over the 50 year period should not be presumed to continue on indefinitely. The large increase in C stocks across the SRS was due primarily to (1) reforestation of agricultural lands, (2) increased stocking on the 1951 woodlands, and (3) active forest management. As of 2001, the SRS forest lands were fully stocked on average, representing the full range of stand conditions that are representative of a sustainable

management prescription. Accordingly, the future changes in C pools across the site will be primarily attributable to management activities (e.g., prescribed fire and harvesting), and management prescriptions that change stand conditions (e.g., composition, age, fertility, rotation).

Models are typically used to assess the change in C balance across a landscape over multiple stand rotations in response to a change in management or use. The data afforded by the 1951 and 2001 forest inventories is a valuable resource to validate forest land assessment tools, and our application of Forest-DNDC demonstrated that use and the additional value that a model can bring to the assessment. In this case, the validated model provided the capability to consider trace greenhouse gases into the assessment. This tool could then be used to assess other alternative on the SRS, or it could also be used with confidence on other similar sites. Fundamentally however, was the demonstration of the importance of the SRS data for model development and testing; there are a host of forest ecosystem models that could benefit from utilizing the SRS data.

The importance and value of long-term ecological monitoring data is often extolled by ecologists; long-term data sets (> 25 years) are rare, the long-term data reported here spanning > 80,000 ha is unique. While the findings on the long-term change in C balance will undoubtedly be received as confirming the perceived values of reforestation and sustainable forest management, expanding the inventory to include soil C would significantly enhance the basis for assessing C dynamics across the landscape. Expanding the basis of the inventoried C pools in conjunction with the landscape level fluxes being measured with the Eddy-covariance tower on the SRS (Kurzeja et al., 2010) will facilitate coupling changes in pools with ecosystem dynamics at multiple temporal and spatial scales.

This work cannot address how future changes in forest management (e.g., intensity of management) or climate change may affect the C balance of the SRS. However, if future experiments on the SRS adequately characterize the change in C balance to a specific treatment or set of conditions, the inventory data summarized here can provide an informed basis for scaling the results as demonstrated by the Forest-DNDC modeling application. Accordingly, the current findings demonstrate the gain in C storage on the SRS over the past 50 years; assessments of future conditions could be considered with simulation tools.

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Appendix A. Conversion factors and measurement equivalents.

1 ha = 2.47 acres	1 Mg dry biomass = 0.5 Mg C
1 in = 2.54 cm	1 cubic ft = 6 board ft
1 Mg = 2205 lbs	1 cubic meter = 35.32 cubic ft
1 Gg = 1000 Mg	1 cord = 2.279 cubic meters
Root:above-biomass = 0.3	Fuel consumption = 4.01 Mg C ha^{-1}
DOC = 5.3 mg l^{-1}	POC = 1.8 mg l^{-1}
Root decay coefficient = 0.0534	TOC = 7.1 mg l^{-1}
Crown coefficient:	Harvest (dry matter):
Pine = 0.1356	Pine = 0.6299 Mg m^{-3}
hardwoods = 0.1793	Hardwood = 0.5726 Mg m^{-3}
Lowland hardwood = 0.2183	Lowland hardwood = 0.5125 Mg m^{-3}

Appendix B-1. Soil organic carbon content from publications reporting SRS data.

Organic matter content (OM%)			Reference
Orangeburg	sandy site	clay site	
0-15cm	0.93±0.28	0.80±0.17	Sanchez et al., 2003
15-30	0.31±0.09	0.17±0.04	
30-45	0.18±0.07	0.13±0.02	
45-60	0.13±0.04	0.23±0.07	

McKee et al., 1983

(28-year)		(8-year)		
	Fuquay	Orangeburg	Wagram	Fuquay
0-7.5cm	0.91	0.40	1.14	1.17
7.5-15	0.75	0.37	0.78	0.76
20-30	0.77	0.43	0.47	0.56
40-50	0.50	0.40	0.38	0.37

Nutter, 1979

Dothan	OM(%)	Fuquay	OM(%)	Norfolk	OM(%)	Troup	OM(%)
0-23cm	1.45	0-30cm	0.75	0-18cm	0.70	0-25cm	1.15
23-81	0.40	30-74	0.40	18-53	0.40	25-76	0.20
81-117	0.20	74-117	0.25	53-89	0.30	76-157	0.15
117-153	0.20	117-165	0.20	89-114	0.20		
				114-170	0.10		

Appendix B-1 (Continued)

Soil type	Year	OM (%)	Odum et al., 1984
Lakeland	1951	1.1	
	1962	-	
	1978-1980	0.84±0.29	
Fuquay	1951	1.1	
	1954	0.90	
	1973	0.91±0.32	
	1978-1980	0.79±0.20	
Eustis	1951	2.0	
	1978-1980	1.5±0.3	
----------In profiles----------			
Lakeland	Depth (cm)	OM (%)	
	0-15	0.7±0.1	
	15-30	0.1±0	
	30-45	0.2±0.2	
	45-60	0.2±0.2	
	60-75	0.1±0.1	
	75-90	0.2±0.2	
	90-105	0.1±0.1	
Eustis			
	0-15	1.3±0.2	
	15-30	0.5±0.1	
	30-45	0.2±0.1	
	45-60	0.4±0.5	
	60-75	0.1±0.1	
	75-90	0.5±0.8	
	90-105	0.2±0.1	

Appendix B-1 Continued

		Odum, 1960
Soil type	soil layer (No. of field)	OM (%)
Lakeland sand (deep phase)	Ap (4)	1.07
	A2	0.15
Lakeland	Ap (8)	1.10
	A2	0.12
Kalnia sand-loam-sand	Ap (7)	0.98
	A2	0.11
Norfolk loamy-sand	Ap (2)	1.45
	B1	0.32
Ruston loamy-sand	Ap (3)	1.00
	B1	0.20
Cahaba loamy-sand	Ap (3)	2.04
	B1	0.55
Myatt sandy-loam	Ap (1)	4.10
	B1	1.14
Izagora sandy-loam	Ap (2)	2.97
	B1	--

Soil	soil layer	crop in 1951	OM in 1951 (%)	OM in 1954 (%)
Kalmia loamy-sand	Ap	cotton	0.92	0.69
	A2		0.08	0.19
Lakeland loamy-sand	Ap	cotton	1.18	0.80
	A2		0.69	0.22
Lakeland sand	Ap	corn	1.31	1.00
	A2		0.17	0.22
Lakeland sand	Ap	cotton	1.07	0.80
	A2		0.26	0.19
Izagora loamy-sand	Ap	peanuts	0.88	0.80
	A2		0.17	0.19
Kalmia sand	Ap	corn	1.18	0.58
	A2		0.10	0.43

Appendix B-1 Continued

					Smith, 2000
	OM (%) in Plantation groups				
	I	II	III	IV	Table No
Plantation site	1.18±0.15	1.14±0.07	1.11±0.06		4.8
Natural sites	3.18±0.23	2.23±0.40	1.46±0.10		4.17
Plantation site	1.07±0.07				4.23
Natural site				3.30±0.26	4.23
Plantation site			1.16±0.06		4.26
Natural site			1.35±0.09		4.26

Appendix B-2. Wetland soil carbon content from site specific study (Dixon et al., 1997)

Core ID	Group#	layer	thick(in)	Test Name	OC (%)
BGW026	3	A	20	TOC	2.47
BGW026		B	20	TOC	2.09
BGW026		C	20	TOC	2.72
BGW026		D	30	TOC	1.11
BGW026		E	30	TOC	0.75
BGW027	1	A	20	TOC	6.12
BGW027		B	20	TOC	5.21
BGW027		C	20	TOC	6.72
BGW027		D	30	TOC	0.14
BGW027		E	30	TOC	0.00976
BGW028	2	A	20	TOC	2.34
BGW028		B	20	TOC	2.42
BGW028		C	20	TOC	1.18
BGW028		D	30	TOC	6.39
BGW028		E	30	TOC	0.178
BGW029	4	A	20	TOC	4.16
BGW029		B	20	TOC	0.94
BGW029		C	20	TOC	0.6
BGW029		D	30	TOC	0.7
BGW029		E	30	TOC	1.42
BGW030	2	A	20	TOC	1.81
BGW030		B	20	TOC	1.22
BGW030		C	20	TOC	0.98
BGW030		D	30	TOC	0.0113
BGW030		E	30	TOC	0.00323
BGW031	3	A	9	TOC	1.22
BGW031		A	9	TOC	1.25
BGW031		B	31	TOC	2.14
BGW031		C	20	TOC	0.58

Appendix B-2 Continued

Dixon et al., 1997

Core ID	Group#	layer	thick(in)	Test Name	OC (%)
BGW031		D	30	TOC	0.086
BGW031		E	30	TOC	0.434
BGW032	4	A	6	TOC	3.18
BGW032		B	34	TOC	1.91
BGW032		C	20	TOC	1.78
BGW032		D	30	TOC	2.13
BGW032		E	30	TOC	1.57
BGW032		E	30	TOC	1.47
BGW033	2	A	20	TOC	8.32
BGW033		B	20	TOC	5.26
BGW033		C	20	TOC	2.02
BGW033		D	30	TOC	0.0133
BGW033		E	30	TOC	0.00825
BGW034	2	A	20	TOC	3.51
BGW034		B	20	TOC	3.24
BGW034		C	20	TOC	0.55
BGW034		D	30	TOC	0.00706
BGW034		E	30	TOC	0.0152
BGW035	1	A	20	TOC	5.79
BGW035		B	20	TOC	4.68
BGW035		C	20	TOC	4.62
BGW035		D	30	TOC	2.36
BGW035		E	30	TOC	0.0291
BGW036	4	A	20	TOC	4.52
BGW036		A	20	TOC	4.21
BGW036		A	20	TOC	3.08
BGW036		B	20	TOC	1.76
BGW036		B	20	TOC	1.17
BGW036		C	20	TOC	1.57
BGW036		C	20	TOC	1.38
BGW036		D	30	TOC	1.8
BGW036		D	30	TOC	1.79
BGW036		E	30	TOC	2.1
BGW036		E	30	TOC	5.11
BGW037	2	A	20	TOC	1.81
BGW037		B	20	TOC	3.35
BGW037		C	20	TOC	0.0755
BGW037		D	30	TOC	0.0229

Appendix B-2 Continued

Dixon et al., 1997

Core ID	Group#	layer	thick(in)	Test Name	OC (%)
BGW037		E	30	TOC	0.00985
BGW038	3	A	20	TOC	0.5
BGW038		B	20	TOC	0.4
BGW038		C	20	TOC	0.58
BGW038		D	30	TOC	1.22
BGW038		E	30	TOC	1.37
BGW039	4	A	20	TOC	3.76
BGW039		B	20	TOC	1.55
BGW039		C	20	TOC	2.07
BGW039		D	30	TOC	2.03
BGW039		E	30	TOC	1.87
BGW039		E	30	TOC	2.05
BGW040	4	A	7	TOC	2.64
BGW040		B	33	TOC	1.35
BGW040		C	20	TOC	2.95
BGW040		D	30	TOC	2.76
BGW040		E	30	TOC	1.38
BGW041	4	A	7	TOC	3.74
BGW041		B	33	TOC	1.1
BGW041		C	20	TOC	1.61
BGW041		D	30	TOC	1.75
BGW041		E	30	TOC	1.66
BGW042	4	A	7	TOC	4.03
BGW042		B	33	TOC	2.07
BGW042		C	20	TOC	2.95
BGW042		D	30	TOC	2.57
BGW042		E	30	TOC	2.28
BGW043	4	A	20	TOC	1.26
BGW043		B	20	TOC	1.1
BGW043		C	20	TOC	0.74
BGW043		D	30	TOC	2.08
BGW043		E	30	TOC	2.03
BGW043		E	30	TOC	2.07
BGW044	4	A	7	TOC	1.1
BGW044		B	33	TOC	0.92
BGW044		C	20	TOC	1.31
BGW044		D	30	TOC	1.25

Appendix B-2 Continued

Dixon et al., 1997

Core ID	Group#	layer	thick(in)	Test Name	OC (%)
BGW044		E	30	TOC	1.15
BGW045	1	A	20	TOC	6.94
BGW045		B	20	TOC	4.34
BGW045		C	20	TOC	1.36
BGW045		D	30	TOC	4.03
BGW045		E	30	TOC	2.32
BGW046	3	A	20	TOC	0.94
BGW046		B	20	TOC	0.231
BGW046		C	20	TOC	0.248
BGW046		D	30	TOC	1.41
BGW046		E	30	TOC	0.78
BGW047	3	A	9	TOC	1.34
BGW047		B	31	TOC	0.25
BGW047		C	20	TOC	0.0237
BGW047		D	30	TOC	0.0254
BGW047		E	30	TOC	0.0202
BGW048	2	A	20	TOC	1.75
BGW048		B	20	TOC	0.78
BGW048		C	20	TOC	0.0127
BGW048		D	30	TOC	0.0127
BGW048		E	30	TOC	1.03
BGW049	3	A	20	TOC	4.72
BGW049		B	20	TOC	1.32
BGW049		C	20	TOC	0.92
BGW049		D	30	TOC	0.88
BGW049		E	30	TOC	1.7
BGW050	2	A	20	TOC	1.37
BGW050		B	20	TOC	0.66
BGW050		C	20	TOC	0.84
BGW050		D	30	TOC	0.25
BGW051	5	A	2	TOC	4.3
BGW051		B	38	TOC	6.5
BGW051		C	20	TOC	3.32
BGW051		D	30	TOC	2.99
BGW051		E	30	TOC	2.88
BGW052	5	A	2	TOC	4.66
BGW052		B	38	TOC	1.8

Appendix B-2 Continued

Dixon et al., 1997

Core ID	Group#	layer	thick(in)	Test Name	OC (%)
BGW052		C	20	TOC	3.63
BGW052		D	30	TOC	1.51
BGW052		E	30	TOC	1.11
BGW053	5	A	2	TOC	4.17
BGW053		B	38	TOC	0.64
BGW053		C	20	TOC	0.189
BGW053		D	30	TOC	0.28
BGW053		E	30	TOC	0.0706
BGW054	5	A	20	TOC	5.32
BGW054		B	20	TOC	1.1
BGW054		B	20	TOC	1.1
BGW054		B	20	TOC	99.5
BGW054		C	20	TOC	0.177
BGW054		D	30	TOC	0.0657
BGW054		E	30	TOC	0.0371
BGW055	5	A	2	TOC	3.43
BGW055		B	38	TOC	4.18
BGW055		C	20	TOC	2
BGW055		D	30	TOC	2.53
BGW055		E	30	TOC	0.021
BGW056	5	A	2	TOC	3.87
BGW056		B	38	TOC	3.56
BGW056		B	38	TOC	3.48
BGW056		C	20	TOC	3.19
BGW056		D	30	TOC	2.95
BGW056		E	30	TOC	2.17
BGW057	5	A	2	TOC	1.35
BGW057		B	38	TOC	1.01
BGW057		C	20	TOC	0.231
BGW057		D	30	TOC	0.116
BGW057		E	30	TOC	0.115
BGW058	5	A	20	TOC	3.45
BGW058		A	20	TOC	3.37
BGW058		B	20	TOC	4.2
BGW058		B	20	TOC	4
BGW058		B	20	TOC	3.96
BGW058		C	20	TOC	2.87

Appendix B-2 Continued

					Dixon et al., 1997
Core ID	Group#	layer	thick(in)	Test Name	OC (%)
BGW058		D	30	TOC	2.73
BGW058		D	30	TOC	1.96
BGW058		E	30	TOC	1.64
BGW058		E	30	TOC	1.7
BGW058		E	30	TOC	0.61
BGW059	5	A	2	TOC	3.68
BGW059		B	38	TOC	4.3
BGW059		C	20	TOC	3.87
BGW059		D	30	TOC	4.28
BGW059		E	30	TOC	3.48
BGW059		E	30	TOC	3.28
BGW060	5	A	20	TOC	9.04
BGW060		B	20	TOC	1.02
BGW060		C	20	TOC	0.217
BGW060		D	30	TOC	0.0656
BGW060		E	30	TOC	0.104
BGW061	3	A	20	TOC	4.34
BGW061		B	20	TOC	1.32
BGW061		C	20	TOC	1.15
BGW061		D	30	TOC	1.06
BGW061		E	30	TOC	0.0118
BGW062	3	A	20	TOC	2.94
BGW062		B	20	TOC	2.12
BGW062		C	20	TOC	2.14
BGW062		D	30	TOC	1.69
BGW062		D	30	TOC	1.66
BGW062		E	30	TOC	0.0483
BGW063	2	A	20	TOC	2
BGW063		B	20	TOC	2.07
BGW063		C	20	TOC	1.43
BGW063		D	30	TOC	0.77
BGW063		E	30	TOC	0.0198
BGW064	3	A	20	TOC	2.42
BGW064		B	20	TOC	1.59
BGW064		C	20	TOC	0.97

Appendix B-2 Continued

Dixon et al., 1997

Core ID	Group#	layer	thick(in)	Test Name	OC (%)
BGW064	D		30	TOC	0.84
BGW064	E		30	TOC	1.09
BGW064	E		30	TOC	1.38
BGW065	A	4	20	TOC	2.16
BGW065	B		20	TOC	1.77
BGW065	C		20	TOC	3.2
BGW065	D		30	TOC	2.24
BGW065	E		30	TOC	2.03
BGW065	E		30	TOC	1.97
BGW066	A	3	20	TOC	0.38
BGW066	A		20	TOC	1.18
BGW066	B		20	TOC	2.56
BGW066	B		20	TOC	3.5
BGW066	C		20	TOC	1.36
BGW066	C		20	TOC	1.2
BGW066	D		30	TOC	1.14
BGW066	D		30	TOC	0.72
BGW066	E		30	TOC	0.64
BGW066	E		30	TOC	0.79
BGW067	A	2	20	TOC	5.17
BGW067	A		20	TOC	4.98
BGW067	B		20	TOC	3.1
BGW067	C		20	TOC	3.27
BGW067	D		30	TOC	1.09
BGW067	E		30	TOC	0.0133
BGW068	A	1	20	TOC	4.52
BGW068	B		20	TOC	5.2
BGW068	C		20	TOC	2.98
BGW068	D		30	TOC	0.173
BGW068	E		30	TOC	0.0234
BGW069	A	1	20	TOC	3.81
BGW069	A		20	TOC	3.47
BGW069	B		20	TOC	1.51
BGW069	B		20	TOC	2.07
BGW069	C		20	TOC	1.2
BGW069	C		20	TOC	1.63
BGW069	D		30	TOC	0.0364

Appendix B-2 Continued

Dixon et al., 1997

Core ID	Group#	layer	thick(in)	Test Name	OC (%)
BGW069	D		30	TOC	0.0482
BGW069	E		30	TOC	0.00841
BGW069	E		30	TOC	0.00578
BGW069	E		30	TOC	0.00583
BGW070	A	1	20	TOC	4.91
BGW070	B		20	TOC	4.53
BGW070	C		20	TOC	4.45
BGW070	D		30	TOC	2.63
BGW070	E		30	TOC	3.84
BGW071	A	1	20	TOC	5.66
BGW071	A		20	TOC	5.39
BGW071	B		20	TOC	3.54
BGW071	C		20	TOC	1.92
BGW071	D		30	TOC	1.22
BGW071	E		30	TOC	0.0247
BGW072	A	1	20	TOC	5.68
BGW072	B		20	TOC	4.35
BGW072	C		20	TOC	3.27
BGW072	D		30	TOC	2.24
BGW072	E		30	TOC	0.0279
BGW073	A	1	20	TOC	1.58
BGW073	B		20	TOC	1.05
BGW073	C		20	TOC	1.78
BGW073	D		30	TOC	0.037
BGW073	E		30	TOC	0.89
BGW074	A	2	20	TOC	3.73
BGW074	A		20	TOC	3.87
BGW074	B		20	TOC	3.04
BGW074	B		20	TOC	3.38
BGW074	C		20	TOC	2.8
BGW074	C		20	TOC	3.55
BGW074	D		30	TOC	0.66
BGW074	D		30	TOC	1.42
BGW074	E		30	TOC	0.0238
BGW074	E		30	TOC	0.0573
BGW074	E		30	TOC	0.0622

Appendix B-2 Continued

Dixon et al., 1997

Core ID	Group#	layer	thick(in)	Test Name	OC (%)
BGW075	A	1	20	TOC	5.43
BGW075	B		20	TOC	2.61
BGW075	C		20	TOC	1.57
BGW075	D		30	TOC	0.0646
BGW075	E		30	TOC	0.0207

Appendix B-3. Upland soil carbon content from SRS studies (Looney et al., 1990)

SERIES	depth (in)	OC (%)
Blanton	0-7	0.587
Blanton	10-65	0.0452
Blanton	65-87	0.0446
Blanton	111-124	0.0284
Blanton	0-6	0.38
Blanton	6-50	0.163
Blanton	50-74	0.041
Blanton	96-120	0.0322
Blanton	0-5	0.308
Blanton	5-52	0.136
Blanton	52-72	0.03
Blanton	96-120	0.038
Blanton	0-7	0.3435
Blanton	7-61	0.03
Blanton	61-70	0.029
Blanton	96-120	0.027
Blanton	0-8	0.4669
Blanton	8-72	0.4838
Blanton	72-84	0.0783
Blanton	96-120	0.0506
Blanton	0-7	0.8842
Blanton	7-60	0.0857
Blanton	60-72	0.1429
Blanton	96-120	0.0573
Blanton	0-6	0.3556
Blanton	6-67	0.213
Blanton	67-77	0.0841
Blanton	96-120	0.086

Appendix B-3 Continued

	Looney et al., 1990	
SERIES	depth (in)	OC (%)
Blanton	0-5	0.4785
Blanton	5-59	0.0563
Blanton	59-72	0.0852
Blanton	96-120	0.0334
Fuquay	0-6	0.326
Fuquay	10-39	0.0597
Fuquay	39-72	0.0646
Fuquay	96-120	0.029
Fuquay	0-8	0.423
Fuquay	8-36	0.054
Fuquay	36-72	0.04
Fuquay	96-120	0.0195
Fuquay	0-6	0.391
Fuquay	6-36	0.127
Fuquay	36-72	0.042
Fuquay	96-120	0.092
Fuquay	0-5	0.4618
Fuquay	5-47	0.0557
Fuquay	47-77	0.0394
Fuquay	96-120	0.0121
Fuquay	0-6	0.5336
Fuquay	6-49	0.0301
Fuquay	49-72	0.1134
Fuquay	96-120	0.0335
Fuquay	0-9	1.109
Fuquay	9-45	0.0936
Fuquay	45-72	0.0545
Fuquay	96-120	0.0219
Fuquay	0-7	1.3146
Fuquay	7-38	0.1172
Fuquay	38-70	0.133
Fuquay	96-120	0.0532
Fuquay	0-9	0.2957
Fuquay	9-41	0.0471
Fuquay	41-72	0.0764
Fuquay	96-120	0.0415

Appendix B-3 Continued

SERIES	depth (in)	OC (%)
Lakeland	0-8	0.777
Lakeland	9-84	0.0477
Lakeland	110-124	0.0202
Lakeland	0-7	0.2573
Lakeland	7-80	0.022
Lakeland	96-120	0.0546
Lakeland	0-5	0.676
Lakeland	5-80	0.0604
Lakeland	96-121	0.0748
Lakeland	0-4	0.4092
Lakeland	4-80	0.0409
Lakeland	96-122	0.0208
Lakeland	0-5	0.0908
Lakeland	5-80	0.4555
Lakeland	96-123	0.072
Lakeland	0-5	0.8843
Lakeland	5-80	0.0436
Lakeland	96-124	0.0632
Lakeland	0-5	1.4493
Lakeland	5-80	0.03
Lakeland	96-125	0.0712
Lakeland	0-9	1.2426
Lakeland	9-80	0.0446
Lakeland	96-126	0.1646
Orangeburg	0-6	0.283
Orangeburg	6-25	0.123
Orangeburg	25-34	0.0967
Orangeburg	34-65	0.0796
Orangeburg	89-103	0.0257
Orangeburg	0-6	0.3219
Orangeburg	6-16	0.1313
Orangeburg	16-34	0.115
Orangeburg	34-60	0.0432
Orangeburg	90-120	0.0487
Orangeburg	0-6	0.548
Orangeburg	6-38	0.184
Orangeburg	38-60	0.09

Appendix B-3 Continued

SERIES	depth (in)	OC (%)
Orangeburg	60-80	0.044
Orangeburg	96-120	0.052
Orangeburg	0-6	0.3661
Orangeburg	6-28	0.187
Orangeburg	28-48	0.0889
Orangeburg	48-60	0.0399
Orangeburg	108-132	0.1176
Orangeburg	0-8	0.2499
Orangeburg	8-20	0.2084
Orangeburg	20-48	0.1106
Orangeburg	48-72	0.0643
Orangeburg	96-120	0.0514
Orangeburg	6-25	0.123
Orangeburg	0-10	0.2725
Orangeburg	10-22	0.0976
Orangeburg	22-50	0.0625
Orangeburg	50-63	0.1034
Orangeburg	96-120	0.044
Orangeburg	0-6	0.3693
Orangeburg	6-20	0.2678
Orangeburg	20-34	0.0865
Orangeburg	34-60	0.1107
Orangeburg	96-120	0.0471
Orangeburg	0-6	0.343
Orangeburg	6-24	0.0619
Orangeburg	24-40	0.2615
Orangeburg	40-68	0.1272
Orangeburg	96-120	0.0305
Udorthent	0-12	0.0316
Udorthent	12-24	0.0192
Udorthent	24-36	0.0183
Udorthent	0-24	0.526
Udorthent	24-48	0.049
Udorthent	48-72	0.0145
Udorthent	0-24	0.0032
Udorthent	24-48	0.0539
Udorthent	48-72	0.0365

Appendix B-3 Continued

SERIES	depth (in)	OC (%)
Udorthent	0-24	0.064
Udorthent	24-48	0.0495
Udorthent	48-72	0.0236
Udorthent	0-24	0.1197
Udorthent	24-48	0.0692
Udorthent	48-72	0.0275
Udorthent	0-24	0.0386
Udorthent	24-48	0.0654
Udorthent	48-72	0.0237
Udorthent	0-24	0.0096
Udorthent	24-48	0.0097
Udorthent	48-72	0.0043
Udorthent	0-24	0.0557
Udorthent	24-48	0.044
Udorthent	48-72	0.0165
Vaucluse	0-23	0.544
Vaucluse	23-65	0.0263
Vaucluse	65-82	0.0487
Vaucluse	95-119	0.0233
Vaucluse	0-22	0.242
Vaucluse	22-59	0.073
Vaucluse	59-74	0.009
Vaucluse	96-120	0.0079
Vaucluse	0-12	0.5703
Vaucluse	12-38	0.0595
Vaucluse	38-72	0.0243
Vaucluse	96-120	0.0189
Vaucluse	0-23	0.0971
Vaucluse	23-50	0.6236
Vaucluse	50-72	0.028
Vaucluse	96-120	0.0192

Appendix B-4. Organic matter in soils at Savannah River Site (NRCS database, 2009)

Series Type	Depth (in) In	Min Bulk density g/cc	Max Bulk density g/cc	OM %
AeB:				
Ailey	0-3	1.4	1.55	0.75
	3-23	1.4	1.55	0.25
	23-30	1.55	1.7	0.15
	30-79	1.7	1.8	0.15
AnB:				
Albany	0-7	1.4	1.55	1.5
	7*54	1.4	1.55	0.25
	54-59	1.5	1.7	0.25
	59-79	1.55	1.65	0.25
Pickney	0-35	1.2	1.4	5
	35-79	1.4	1.6	3
Williman	0-8	1.5	1.7	1.75
	8*28	1.5	1.7	0.25
	28-58	1.3	1.5	0.25
	58-79	1.45	1.55	0.25
BaB:				
Blanton	0-5	1.3	1.6	0.75
	5*54	1.3	1.6	0.75
	54-74	1.6	1.7	0.25
	74-79	1.6	1.7	0.25
BaC:				
Blanton	0-5	1.3	1.6	0.75
	5*54	1.3	1.6	0.75
	54-74	1.6	1.7	0.25
	74-79	1.6	1.7	0.25
Ch:				
Chastain	0-2	1.2	1.4	4
	2*45	1.3	1.5	0.25
	45-54	1.3	1.5	0.25
	54-58	1.35	1.45	0.25
	58-79	1.5	1.6	0.25
Da:				
Dorovan	0-12	0.25	0.4	79.5
	12*58	0.35	0.55	60
	58-79	1.35	1.45	6.5

Appendix B-4 Continued

Series Type	Depth (in) In	Min bulk density g/cc	Max bulk density g/cc	OM %
DoA:				
Dothan	0-8	1.3	1.6	0.5
	8*11	1.3	1.6	0.25
	11*31	1.4	1.6	0.25
	31-79	1.45	1.7	0.25
DoB:				
Dothan	0-8	1.3	1.6	0.5
	8*11	1.3	1.6	0.25
	11*31	1.4	1.6	0.25
	31-79	1.45	1.7	0.25
EnA:				
Eunola	0-8	1.45	1.7	1.25
	8*15	1.45	1.7	0.25
	15-30	1.35	1.65	0.25
	30-55	1.3	1.6	0.25
	55-79	1.35	1.65	0.25
Williman	0-8	1.5	1.7	1.75
	8*28	1.5	1.7	0.25
	28-58	1.3	1.5	0.25
	58-79	1.45	1.55	0.25
Fa:				
Fluvaquents	0-4	1.2	1.4	5
	4*79	1.4	1.6	3
FuA:				
Fuquay	0-8	1.6	1.7	1.25
	8*21	1.45	1.55	0.25
	21-35	1.4	1.6	0.25
	35-79	1.4	1.6	0.25
FuB:				
Fuquay	0-8	1.6	1.7	1.25
	8*21	1.45	1.55	0.25
	21-35	1.4	1.6	0.25
	35-79	1.4	1.6	0.25

Appendix B-4 Continued

Series Type	Depth (in) In	Min bulk density g/cc	Max bulk density g/cc	OM %
FuC:				
Fuquay	0-8	1.6	1.7	1.25
	8*21	1.45	1.55	0.25
	21-35	1.4	1.6	0.25
	35-79	1.4	1.6	0.25
HoA:				
Hornsville	0-6	1.44	1.68	2.5
	6*49	1.58	1.63	0.25
	49-79	1.62	1.69	0.15
Rembert	0-7	1.3	1.5	3
	7*30	1.2	1.5	0.25
	30-42	1.3	1.5	0.25
	42-79	1.3	1.6	0.25
Kn:				
Kinston	0-3	1.3	1.5	3
	3*28	1.3	1.5	0.8
	28-42	1.3	1.5	0.8
	42-79	1.3	1.5	0.8
LaB:				
Lakeland	0-66	1.35	1.65	0.75
	66-79	1.5	1.6	0.25
LaC:				
Lakeland	0-66	1.35	1.65	0.75
	66-79	1.5	1.6	0.25
LuA:				
Lucy	0-9	1.3	1.7	0.75
	9*26	1.3	1.7	0.5
	26-31	1.4	1.6	0.25
	31-79	1.4	1.6	0.25
LuB:				
Lucy	0-9	1.3	1.7	0.75
	9*26	1.3	1.7	0.5
	26-31	1.4	1.6	0.25
	31-79	1.4	1.6	0.25

Appendix B-4 Continued

Series Type	Depth (in) In	Min bulk density g/cc	Max bulk density g/cc	OM %
LuC:				
Lucy	0-9	1.3	1.7	0.75
	9*26	1.3	1.7	0.5
	26-31	1.4	1.6	0.25
	31-79	1.4	1.6	0.25
NeB:				
Neeses	0-5	1.45	1.55	0.75
	5*8	1.45	1.55	0.25
	8*28	1.3	1.6	0.25
	28-54	1.7	1.9	0.15
	54-79	1.55	1.75	0.15
NoA:				
Norfolk	0-11	1.3	1.6	0.75
	11*50	1.35	1.75	0.25
	50-79	1.75	1.95	0.25
NoB:				
Norfolk	0-11	1.3	1.6	0.75
	11*50	1.35	1.75	0.25
	50-79	1.75	1.95	0.25
Oa:				
Ochlockonee	0-6	1.4	1.6	1.25
	6*38	1.4	1.6	0.25
	38-79	1.45	1.55	0.25
OcA:				
Ocilla	0-7	1.3	1.65	1.5
	7*24	1.5	1.6	0.25
	24-55	1.2	1.45	0.25
	55-79	1.25	1.5	0.25
OcA:				
Pickney	0-35	1.2	1.4	5
	35-79	1.4	1.6	3
Og:				
Ogeechee	0-8	1.35	1.45	1.5
	8*15	1.45	1.55	0.25
	15-45	1.55	1.65	0.25
	45-79	1.55	1.65	0.25

Appendix B-4 Continued

Series Type	Depth (in) In	Min bulk density g/cc	Max bulk density g/cc	OM %
OrA:				
Orangeburg	0-6	1.35	1.55	0.75
	6*24	1.6	1.75	0.25
	24-79	1.6	1.75	0.25
OrB:				
Orangeburg	0-6	1.35	1.55	0.75
	6*24	1.6	1.75	0.25
	24-79	1.6	1.75	0.25
OrC:				
Orangeburg	0-6	1.35	1.55	0.75
	6*24	1.6	1.75	0.25
	24-79	1.6	1.75	0.25
Pk:				
Pickney	0-35	1.2	1.4	5
	35-79	1.4	1.6	3
Rm:				
Rembert	0-7	1.3	1.5	3
	7*30	1.2	1.5	0.25
	30-42	1.3	1.5	0.25
	42-79	1.3	1.6	0.25
Sh:				
Shellbluff	0-5	1.2	1.45	1.75
	5*34	1.2	1.5	0.25
	34-79	1.2	1.5	0.25
Chastain	0-2	1.2	1.4	4
	2*45	1.3	1.5	0.25
	45-54	1.3	1.5	0.25
	54-58	1.35	1.45	0.25
	58-79	1.5	1.6	0.25
Sm:				
Smithboro	0-6	1.2	1.4	1.75
	6*17	1.3	1.6	0.25
	17-79	1.3	1.6	0.25
Rembert	0-7	1.3	1.5	3
	7*30	1.2	1.5	0.25
	30-42	1.3	1.5	0.25
	42-79	1.3	1.6	0.25

Appendix B-4 Continued

Series Type	Depth (in) In	Min bulk density g/cc	Max bulk density g/cc	OM %
Ta:				
Tawcaw	0-5	1.35	1.45	1.5
	5*58	1.3	1.4	0.25
	58-79	1.3	1.4	0.25
Kinston	0-3	1.3	1.5	3
	3*28	1.3	1.5	0.8
	28-42	1.3	1.5	0.8
	42-79	1.3	1.5	0.8
Pickney	0-35	1.2	1.4	5
	35-79	1.4	1.6	3
To:				
Toccoa	0-9	1.35	1.45	1.5
	9*17	1.4	1.5	0.25
	17-60	1.4	1.5	0.25
	60-79	1.4	1.5	0.25
Chastain	0-2	1.2	1.4	4
	2*45	1.3	1.5	0.25
	45-54	1.3	1.5	0.25
	54-58	1.35	1.45	0.25
	58-79	1.5	1.6	0.25
TrB:				
Troup	0-2	1.3	1.7	0.75
	2*60	1.3	1.7	0.25
	60-79	1.4	1.6	0.25
TrC:				
Troup	0-2	1.3	1.7	0.75
	2*60	1.3	1.7	0.25
	60-79	1.4	1.6	0.25
TrD:				
Troup	0-2	1.3	1.7	0.75
	2*60	1.3	1.7	0.25
	60-79	1.4	1.6	0.25
Lucy	0-9	1.3	1.7	0.75
	9*26	1.3	1.7	0.5
	26-31	1.4	1.6	0.25
	31-79	1.4	1.6	0.25

Appendix B-4 Continued

Series Type	Depth (in) In	Min bulk density g/cc	Max bulk density g/cc	OM %
TuE:				
Troup	0-2	1.3	1.7	0.75
	2*60	1.3	1.7	0.25
	60-79	1.4	1.6	0.25
TuE:				
Lucy	0-9	1.3	1.7	0.75
	9*26	1.3	1.7	0.5
	26-31	1.4	1.6	0.25
	31-79	1.4	1.6	0.25
TuF:				
Troup	0-2	1.3	1.7	0.75
	2*60	1.3	1.7	0.25
	60-79	1.4	1.6	0.25
Lucy	0-9	1.3	1.7	0.75
	9*26	1.3	1.7	0.5
	26-31	1.4	1.6	0.25
	31-79	1.4	1.6	0.25
Ud:				
Udorthents	0-79	1.3	1.65	0.5
Uo:				
Udorthents	0-79	1.3	1.65	0.5
Ur:				
Udorthents	0-79	1.3	1.65	0.5
VaB:				
Vaucluse	0-3	1.3	1.6	0.75
	3*10	1.3	1.6	0.25
	10*22	1.35	1.75	0.25
	22-60	1.75	1.95	0.25
	60-79	1.55	1.9	0.25
VeC:				
Vaucluse	0-3	1.3	1.6	0.75
	3*10	1.3	1.6	0.25
	10*22	1.35	1.75	0.25
	22-60	1.75	1.95	0.25
	60-79	1.55	1.9	0.25

Appendix B-4 Continued

Series Type	Depth (in) In	Min bulk density g/cc	Max bulk density g/cc	OM %
Ailey	0-3	1.4	1.55	0.75
	3*22	1.4	1.55	0.25
	23-30	1.55	1.7	0.15
	30-79	1.7	1.8	0.15
VeD:				
Vaucluse	0-3	1.3	1.6	0.75
	3*10	1.3	1.6	0.25
	10*22	1.35	1.75	0.25
	22-60	1.75	1.95	0.25
	60-79	1.55	1.9	0.25
VeD:				
Ailey	0-3	1.4	1.55	0.75
	3*23	1.4	1.55	0.25
	23-30	1.55	1.7	0.15
	30-79	1.7	1.8	0.15
WaA:				
Wagram	0-9	1.6	1.75	1.25
	9*22	1.6	1.75	1.25
	22-79	1.4	1.5	0.25
WaB:				
Wagram	0-9	1.6	1.75	1.25
	9*22	1.6	1.75	1.25
	22-79	1.4	1.5	0.25
Wm:				
Williman	0-8	1.5	1.7	1.75
	8*28	1.5	1.7	0.25
	28-58	1.3	1.5	0.25
	58-79	1.45	1.55	0.25