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Environmental Pollution 116 (2002) 373–380

ENVIRONMENTAL
POLLUTION

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Methodology for estimating soil carbon for the forest carbon budget model of the United States, 2001

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Received 1 July 2001; accepted 24 July 2001

"Capsule": *Development of soil C pool estimates for the FORCARB model.*

Abstract

The largest carbon (C) pool in United States forests is the soil C pool. We present methodology and soil C pool estimates used in the FORCARB model, which estimates and projects forest carbon budgets for the United States. The methodology balances knowledge, uncertainties, and ease of use. The estimates are calculated using the USDA Natural Resources Conservation Service STATSGO database, with soil dynamics following assumptions based on results of site-specific studies, and area estimates from the USDA Forest Service, Forest Inventory and Analysis data and national-level land cover data sets. Harvesting is assumed to have no effect on soil C. Land use change and forest type transitions affect soil C. We apply the methodology to the southeastern region of the United States as a case study. Published by Elsevier Science Ltd.

Keywords: Carbon cycle; Climate change; FORCARB; Land use change; Forest inventory

1. Introduction

National-level forest carbon (C) budgets are needed for scientific understanding and policy debates. Carbon in forests occurs in a number of pools: live tree, dead tree, harvested wood, down dead wood, forest floor, and soil C. One approach for estimating these broad-scale budgets is to combine measured forest inventory data with models to account for other pools of forest C that are not measured. Forest inventory techniques are based on sample designs with a sound scientific basis, and have been operationally implemented to measure aboveground tree volumes with satisfactory results (Schreuder et al., 1993). Because the inventories have not traditionally measured C directly, known relationships between tree diameter and C content for individual tree species are used to estimate tree C. Similar relationships are the standard method used to estimate wood volume from these measured data (Wenger, 1984). Other forest C pools, such as the forest floor and soil C, traditionally have not been sampled in the broad-scale inventory. To estimate C in these pools, models are developed based on available information, including tested hypotheses and data from site-specific studies. This approach has been adopted to produce forest C estimates for countries such as the United States (Heath and Birdsey, 1993; Plantinga and Birdsey, 1993; Turner et al., 1995), Canada (Kurz et al., 1995), Russia (Alexeyev et al., 1995), and European countries (Nabuurs et al., 1997). In the future, the sampling design for forest inventories of the United States includes measurements of forest floor C and soil C (USDA Forest Service, 2001), but these data will not be available for a number of years.

The purpose of this study is to present the updated methodology behind the soil C estimates used in a carbon budget model for the forest sector of the United States. The update includes information from databases that have become recently available, recent forest vegetation GIS coverages, and information from new scientific studies that have been published in the last 10 years. We present base estimates of soil C associated with forests, and discuss forest type transition, harvesting and land use change effects on soil C. The methodology is applied using the southeastern region of the United States as a case study.

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0269-7491/01/$ - see front matter Published by Elsevier Science Ltd.
PII: S0269-7491(01)00213-5

2. Methods

2.1. Model framework

In this study, the model framework is based on classifications used by forest inventories (as opposed to soil inventory classifications) due to the purposes of the forest C budget. Estimates from forest inventories are usually reported in categories with similar features that are convenient to use, such as categories describing the location of the trees (region), vegetation type (forest type), productivity (e.g. high or low), and ownership (which affects forests because of general management differences between owner groups). The southeastern region includes the States of Florida, Georgia, South Carolina, North Carolina, and Virginia.

We are interested in accounting for mineral soil C changes due to harvesting, forest type transitions, and land use changes of afforestation and deforestation. Only clearcut harvesting is considered. A forest type transition is the change of forest types on a site, such as an oak–hickory type being converted to a planted pine type. Land use change results not only in a slow accumulation of soil C following afforestation or a relatively quick loss following deforestation, but also results in the accounting transfer of the mineral soil C into the forest sector from agriculture, or from the forest sector to agriculture. This large transfer should not be interpreted as a C exchange with the atmosphere; therefore, it is important to be clear about how these transfers are handled in C estimation.

2.2. Previous soil C estimates

Our previous soil C stock estimates were derived from regression equations for estimating soil organic C from temperature, moisture, and texture in Burke et al. (1989). These equations were used to develop soil C estimates for forest originating on cropland, pasture, or forest. Only afforestation was counted in this approach because, at the time, we were only counting carbon on forest lands. After clearcut harvest, soil C was assumed to decline up to 20% over a 10–15 year period following harvest and to accumulate gradually to a base forest C level by time of forest maturity (approximately 50 years). For more information about previous forest soil C estimates used in the United States forest C model, see Birdsey (1992), Birdsey and Heath (1995), and Heath and Smith (2000).

2.3. Estimating undisturbed soil C inventory

We assumed that forest soils reach approximately a steady-state after a long period with no major disturbance. Undisturbed stocks of soil C can be estimated by two approaches: (1) analysis of soils databases, and (2) simulation using a mechanistic model of soil processes. We chose the first approach because of the ready availability of the STATSGO (State Soil Geographic) database, which was developed by the USDA Natural Resources Conservation Service. STATSGO is a set of state maps of soil attributes developed for use with a GIS. State-level maps were digitized from higher resolution base maps of the phases of available soil series. For the present study, we generated geo-referenced estimates of soil organic C content (Mg/ha) for each state from attribute data on percent C, soil texture, bulk density, and content of large and small rock fragments, using methods described in Bliss et al. (1995). We estimated C content for mineral soil depths of 0–25 cm, where the C concentration is generally thought to be greatest, and 0–100 cm, which probably includes most C in a typical soil column. Raster maps of soil organic C content were produced at a resolution of 1 km to correspond to the resolution of available forest type group maps. Estimates of soil C were derived by overlaying the soil C coverage with the coverage of forest type groups developed from AVHRR satellite imagery by the USDA Forest Service, FIA (Zhu and Evans, 1992). Mineral soil C values then were extracted from pixels for each forest type and averaged by region.

In our estimates, we included Histosols (organic soils), which are typical of bogs and wetlands, similar to the approach of Xu and Prisley (2000). Our reason for including these soils was because forests that contain bogs and wet areas of less than one acre are classified as forest land. We assumed that the estimates would be more accurate by including the Histosols in forested areas.

To check the values, we collected studies from the recent literature that included estimates of soil C content from a variety of forest types. We extrapolated C estimates, which covered a wide range of depths in the literature, to depths of 0–25 and 0–100 cm so that they would be directly comparable with our STATSGO-based estimates. The extrapolation was performed by estimating soil C density per 1 cm depth for the results reported in each study, and then the densities were multiplied by either 25 or 100 cm, respectively, for a soil C total.

2.4. Soil C dynamics

We considered using a mechanistic model of soil processes to estimate soil C changes. However, using such a model to produce regional estimates presented considerable challenges. CENTURY (Parton et al., 1987, 1993) is arguably the most maturely developed and best tested of such models and would be a good candidate for our study. The detailed nature of the model's processes requires reasonable estimates of many parameters (e.g. soil texture, bulk density, soil pH, soil C content

Table 1
Estimates of mean soil carbon and variability at two depths from the STATSGO soils database for forest type groups in the southeastern United States

Forest type group	Area (ha×1000)	Mean soil C (0–0.25 m; Mg/ha)	Standard deviation	Mean soil C (0–1 m; Mg/ha)	Standard deviation
White-red-jack pine	166	34	21	42	36
Spruce–fir	15	53	45	71	67
Longleaf–slash pine	6381	59	53	166	203
Loblolly–shortleaf pine	9184	30	40	75	160
Oak–pine	6438	30	28	61	106
Oak–hickory	6955	28	20	45	70
Oak–gum–cypress	7197	64	54	182	231
Maple–beech	185	35	33	49	56
Nonforest	22,851	39	41	98	159

for the 0–20 cm layer), initial values of several input variables (e.g. N input), and weather variables. Thus, considerable knowledge of an individual site is necessary to permit the model to simulate it with accuracy. Because we required many such sites for our estimates of soil C changes in different forest types and regions, the time needed for initial data gathering and running of the model made its use impractical. In addition, the results of a recent broad-scale study (Giardina and Ryan, 2000) suggest that measured data from forests conflict with results based on established modeling assumptions concerning soil C turnover and storage. Because of these uncertainties in the fundamental assumptions of a modeling approach, and the time constraint previously noted, we chose to base our estimates on measured data, and adopted simple assumptions.

2.5. Area estimation of afforestation and deforestation

To apply the effects of land use change, another requisite was the area of forest that was previously nonforest. Land use changes involve shifts between major land use/land cover categories: forest, agriculture, and developed. We explored data sources for gross changes (afforestation and deforestation) in area.

Land use data are available from the USDA Natural Resources Conservation Service, National Resource Inventories (NRI), but areas of forest and forest types are available from the USDA Forest Service, Forest Inventory and Analysis (FIA). The NRI data are available periodically for 1945–1997; forest inventory data from FIA were periodically collected and reported from 1953 to 1997. These data may produce different areal estimates because they are different samples, hence the differences must be reconciled to use these data together. We compiled data from available sources (USDA Forest Service, 1958, 1965, 1977, 1988; US Bureau of the Census, 1977; Waddell et al., 1989; Daugherty, 1995; Smith et al., in press), and minimized the errors of their differences. In this study, we focus on the southeastern United States to illustrate the methods.

3. Results

3.1. Estimating baseline C levels

Averages of soil C content for the two mineral soil depths by forest type and aggregated to the regional level are given in Table 1. A general caveat to using STATSGO to estimate C content of forest soils is that the database was developed primarily from agricultural soil series. Thus, the extension of a soil series into forested land generally represents an extrapolation assuming similar characteristics under forest and crop cover. Clearly, mineral soils under such different forest types and land uses may be very different, especially with respect to C content.

Because we were concerned about the applicability of STATSGO data to forest soils, we compared the soil C values estimated from the database with those from studies in the recent literature. We reviewed studies that included estimates of soil C content from a variety of forest types for the southeast (Table 2). We extrapolated C estimates, which covered a wide range of depths in the literature, to depths of 0–25 and 0–100 cm so that they would be comparable with our STATSGO estimates. Although there was large variability of the STATSGO estimates, the published literature data were within one standard deviation of the mean STATSGO estimates.

The method used in this study does not produce a soil C value for the nonstocked forest type. Nonstocked forest is not the same as non-forest. A nonstocked area is defined as productive forest that is less than 10% stocked with trees of a minimum size. Recently harvested areas may be considered nonstocked. We estimated what forest type the nonstocked areas would have been had they met the stocking requirement, and then used the soil C value listed for that type in Table 1.

3.2. Soil C dynamics

Several recent reviews have considered soil C dynamics following forest harvest, deforestation for cultivation

Table 2
Published estimates of soil carbon from individual studies in the southeastern United States

State[a]	Reference	Stand composition	Forest age (year)	FIA[b] forest type group	Soil texture	Soil carbon (0–0.25 m; Mg/ha)	Soil carbon (0–1 m; Mg/ha)
NC	Mattson and Swank (1989)	Oak, hickory, red maple, yellow poplar	>50	OH	Coarse loam	38	95
SC	Binkley et al. (1992)	Loblolly and longleaf pines	~ 50	LLP	Fine loamy silicaceous	64	–
FL	Harding and Jokela (1994)	Slash pine plantation	25	LLP	Loamy fine sand	38	106
GA	Huntington (1995)	Oak, hickory, yellow poplar, loblolly pine	60–80	OH	Sandy loam	51	82
GA	Huntington (1995)	Oak, hickory, yellow poplar, loblolly pine	Old-growth	OH	Sandy loam	75	122

[a] NC, North Carolina; SC, South Carolina; FL, Florida; GA, Georgia.
[b] FIA is the USDA Forest Service, Forest Inventory and Analysis. Forest types are: OH, Oak–Hickory, and LLP, Loblolly Pine.

or pasture, and afforestation (Johnson, 1992; Heath and Smith, 2000; Post and Kwon, 2000; Johnson and Curtis, 2001). One main generality that can be drawn from the reviews is that experimental studies of the topics need to be designed to test the specific hypothesis of interest. A second generality is that soil C dynamics may be highly site specific, or highly variable, or perhaps both.

3.2.1. Dynamics following forest harvest and forest type transition

Harvesting, including clearcutting, is generally thought to result in little change in soil C if the forest is regenerated immediately (Schlesinger, 1986). In a review of 13 published studies, Johnson (1992) reported that 11 studies found no significant changes in soil C following harvest. This implies no effect of forest age on soil C, which is a strong conclusion in Grigal and Ohmann (1992). The remaining studies, which found changes, were on a tropical forest in Ghana and a Eucalypt forest in Tasmania, and are probably not applicable to our study. In an updated review and meta-analysis, Johnson and Curtis (2001) reviewed 26 studies and again found no conclusive trends to relate harvesting and soil C dynamics. The studies centered on zero change, with most results lying in the range of about 25% increase and 25% decrease in soil C. However, the analysis revealed that harvesting method affects C storage fairly consistently. Harvest of sawlogs only led to an increase in soil C, whereas whole tree harvest led to a slight decrease.

These studies indicate that empirical evidence is lacking for consistent changes in average organic C stocks in the mineral soil following harvesting and immediate regeneration. Because of the lack of strong evidence for a clear trend, we assume in our model that soil C does not change due to harvest. That is, the soil C estimates in Table 1 are used for the appropriate forest type after harvest, regardless of forest age if regeneration is immediate and if no land use change or forest type transition has occurred on the site. However, if regeneration results in a different forest type than was harvested and it is possible to track the area, we assume a linear transition over 50 years from the soil C estimate of the old forest type to the estimate of the new type.

3.2.2. Dynamics following land use change: deforestation and cultivation

Deforested lands in the United States are usually converted to urban and developed uses or pastures, or are cultivated for cropland. Cultivation of soils in temperate regions results in an average loss of soil C of 30% from the entire soil solum (Davidson and Ackerman, 1993). Cultivation of forested lands usually results in a rapid loss of soil C in the first 20 years, followed by loss at a lower rate as a new equilibrium level is approached (Mann, 1986). Schlesinger (1986) concluded that the loss of C from forest soils with cultivation is about 30% and that the loss occurs over a 20–50 year interval. The interpretation of published results may be confounded by an "initial C effect" (Mann, 1986). In soils with high initial levels of C, a loss of about 20% may be expected under cultivation. In soils with low initial levels, there may be slight gains of C in some cases. Based on these studies, Houghton and Hackler (2000) assumed that cultivation led to a 25% reduction in soil C in the first 15 years of cultivation. They assumed that soil C was not affected by conversion to pasture with no cultivation, and moreover most pastures were found on natural grasslands.

Based on Davidson and Ackerman (1993), we assumed that conversion of forest land to cultivated land would result in a 30% loss of C. Conversion of forest land to pasture may occur without cultivation, and no cultivation probably means less soil C loss. However, unlike Houghton and Hackler we do expect that a noticeable amount of forest land in some regions would be converted to pastures. We assumed that conversion to pasture results in a 15% loss. Losses should be constant over a 25-year time frame until the new steady-state C level is reached. There was no overwhelming evidence that decreases followed a linear or an exponential trajectory. Thus, we assumed a linear decrease because it was easier to apply in our model framework. We found no studies that indicated the effect of conversion of forest land to urban and developed uses. Moreover, in forest inventories, forest land may be classified as under an urban and developed use when only a small portion of the area has been cleared. For example, building a house in a small clearing in a forested area will result in a large area being transferred into urban use in the forest inventory statistics; however, only a very small area of forest is actually affected. However, soils in developed areas may be greatly disturbed when actually deforested. Therefore, we assumed that when the loss of soil C is averaged over the entire area that is considered deforested for urban use, about 15% of mineral soil C is lost over a 10-year time frame.

3.2.3. Dynamics following land use change: reforestation and afforestation

Reforestation of abandoned cultivated land generally results in a build-up of soil C, although the process may be a slow one, often requiring from 10 to as many as 200 years (Post and Kwon, 2000). Compton et al. (1998) compared soil C in central Massachusetts in abandoned, formerly cultivated sites and in sites that were never plowed. Agricultural sites abandoned for 40–60 years and allowed to regenerate had 36% less soil C than uncultivated sites, suggesting that more than 50 years may be necessary for cultivated soils to recover former C levels. Conversely, Pregitzer and Palik (1996) reported very little change or slight decreases in soil C after over 40 years under pines planted on degraded agricultural soils in Michigan. A more widely reported pattern is an initial decrease in soil C immediately after forest establishment followed by a long-term increase. Investigating patterns of old field succession, Zak et al. (1990) observed an initial loss of soil C for about 10 years after abandonment followed by a steady rise over the subsequent 50 years. Although this is a plausible trend, it must be emphasized that their study included only old fields with grasses and herbaceous vegetation and not regenerating forests. A 40-year study of a pine plantation growing on previously cultivated land similarly found an initial decrease in soil C for about 10 years followed by a steady rise (Richter et al., 1999). However, that pattern was seen only in the top 7.5 cm of mineral soil; lower horizons to a depth of 60 cm showed no gains in C. A similar pattern of initial decrease and subsequent increase in soil C was observed in aspen plantations on previously cultivated land (Hansen, 1993). Four- to six-year-old plantations had less C in upper soil horizons than adjacent cultivated plots. However, plantations averaging 15 years contained more C than adjacent cultivated plots. Houghton and Hackler (2000) assumed that following afforestation, soil C accumulated rapidly during the first 50 years and then slowly for the next 100 years. Soil C was assumed not to change following conversion from pasture to forest because the results were highly variable and there was a suggestion that most pastures were natural grasslands.

For modeling purposes, it is probably safe to adopt the simplifying assumption that soils afforested after cultivation begin accumulating C immediately and continue to do so until an approximate steady state is attained. Using the converse of the general estimate for effects of deforestation, we assume that cropland soils being afforested start at tree establishment with 30% less C than the average for their forest type and pasture soils being afforested start with 15% less C than average. For example, our estimate of soil C in cultivated land being converted to maple–beech–birch forest in the northeast region would be 81 Mg/ha (i.e. 0.7×116 from Table 1). We assume that the soil C on afforested land increases at a constant rate until it reaches the magnitude estimated to occur on forested land. Adopting a constant rate makes it possible to apply the change in the model. The increase occurs over a specified time period in all cases. Table 3 summarizes the mineral soil C estimates and dynamics for the southeastern region of the United States.

3.3. Land use change areal estimates: an example

We chose to use the southeastern United States for a case study of estimating mineral soil C changes because

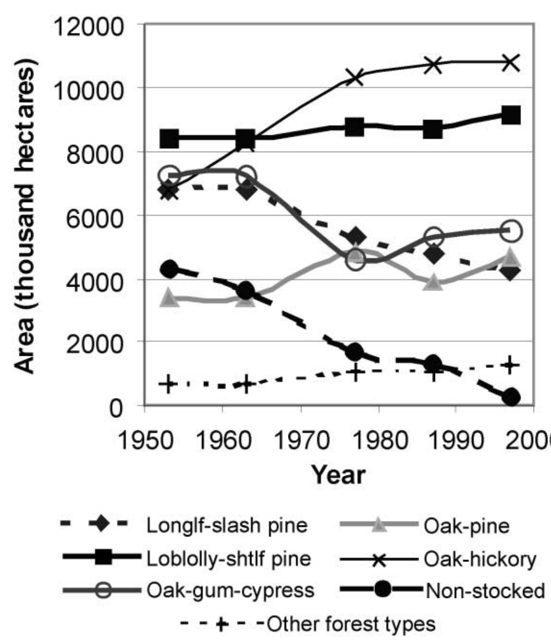

Fig. 1. Area (1000 ha) of forest types in the southeastern United States, 1953–1997.

Table 3
Summary of parameters used in estimating mineral soil carbon, and carbon dynamics due to land use change, southeastern United States[a]

Forest type	Carbon in mineral soil (Mg C/ha)				Mineral soil carbon change (Mg C/ha/year)				
	Undisturbed	Cropland	Pasture	Developed	Crop to forest	Pasture to forest	Forest to crop	Forest to pasture	Forest to developed
Longleaf Pine	166	116	141	141	0.5	0.5	−2.0	−1.0	−2.5
Loblolly Pine	75	53	64	64	0.2	0.2	−0.9	−0.4	−1.1
Oak–Pine	61	43	52	52	0.1	0.1	−0.7	−0.4	−0.9
Oak–Hickory	45	32	38	38	0.3	0.3	−0.5	−0.3	−0.7
Oak–Gum–Cypress	182	127	155	155	0.7	0.7	−2.2	−1.1	−2.7

[a] A negative change value indicates carbon is being emitted to the atmosphere. Land changing from cropland to forest is assumed to accrue carbon for 100 years; land changing from pasture to forest is assumed to accrue carbon for 50 years. Soil carbon loss following deforestation occurs in the first 25 years following conversion to crop and pasture, and in the first 10 years following conversion to developed.

Table 4
Afforestation summary for forest land in non-industrial private ownership in the southeastern United States, 1953–1997

Forest type	1987–1997			1977–1986			1963–1976			1953–1962		
	Crop.	Past.	Dev.	Crop.	Past.	Dev.	Crop.	Past.	Dev.	Crop.	Past.	Dev.
Longleaf Pine	176.1	160.6	43.0	122.7	89.0	21.4	72.3	168.8	19.8	246.4	105.6	9.5
Loblolly Pine	461.4	420.9	112.8	246.8	179.0	43.0	145.4	339.4	39.9	495.4	212.3	19.1
Oak–Pine	84.3	76.9	20.6	33.4	24.2	5.8	19.7	45.8	5.4	66.9	28.7	2.6
Oak–Hickory	96.0	87.6	23.5	116.4	84.5	20.3	68.6	160.1	18.8	233.7	100.2	9.0
Oak–Gum–Cypress	40.0	36.5	9.8	30.8	22.4	5.4	18.2	42.4	5.0	61.9	26.5	2.4
Other	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nonstocked	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	857.8	782.5	209.7	550.2	399.0	95.9	324.2	756.5	88.9	1104.3	473.3	42.5

Total area (1000 ha) of forest land converted from non-forest use of cropland, pasture, and developed use, by forest type.

land use change data was more accessible. The pattern of area of major forest types is shown in Fig. 1 over the years 1953–1997. In the early years of this period, a substantial portion of the forest area was designated as nonstocked, probably due to livestock grazing and burning to encourage forage for grazing. As grazing declined, the areas became forested, with much of the area shifting to oak–hickory. Longleaf-slash pine forest type area declined as areas became developed and shifted types.

Total area, such as that shown in Fig. 1, mask the dynamics of afforestation and deforestation that occur in every type. Our estimates for afforestation and deforestation are given by forest type for non-industrial private owners in Tables 4 and 5. Results for other ownerships are not shown because they featured little land use change. Only about 5% of the land use change involving forest land in the southeastern United States over this period was in public or industrial ownership. In total over the 44-year period, 5.9 million ha were afforested; about 8.0 million ha were deforested. About 130,000 ha were afforested annually on non-industrial private forest land ownerships while an estimated 170,000 ha were deforested over the 44-year period. Approximately 50% of deforestation was for developed uses, while 25% of deforestation was for cropland and pasture, respectively. Conversely, very little (8%) developed land was afforested; approximately 50% of afforestation came from cropland and 42% came from pasture. The greatest afforestation and deforestation in a forest type occurred in the loblolly pine forest type. For this analysis, we assumed that the afforested area remained in forest over the period and deforested areas remained deforested. This assumption is supported by estimates from the NRI data for the period 1987–1997, which indicated only 2% of the areas sampled in 1987 switched to non-forest use in 1992, and back to forest use at the time of the next survey.

In addition to afforestation and deforestation, according to our estimates, soil C must be sequestered or emitted due to forest type transition. For example, about 4% of the area of longleaf pine in the southeast (166 Mg C/ha; 0–100 cm depth) in 1997 was designated as oak–pine (61 Mg C/ha; 0–100 cm depth) in 1987. Soil C estimates summarized by forest type imply that in this example transition will result in an eventual gain of 105 Mg C/ha of soil C. Fortunately, preliminary calculations indicated that there were only minor shifts in forest types transitions between types of high and low mineral soil C.

Table 5
Deforestation summary for forest land in non-industrial private ownership in the southeastern United States, 1953–1997

Forest type	1987–1997			1977–1986			1963–1976			1953–1962		
	Crop.	Past.	Dev.	Crop.	Past.	Dev.	Crop.	Past.	Dev.	Crop.	Past.	Dev.
Longleaf Pine	25.7	34.9	152.7	37.3	38.7	125.7	80.1	34.3	114.5	38.3	89.3	54.7
Loblolly Pine	68.2	93.2	408.5	129.3	134.2	435.2	277.3	118.8	396.7	132.5	309.3	189.6
Oak–Pine	24.0	32.6	142.9	35.0	36.3	117.7	75.0	32.1	107.3	35.8	83.6	51.3
Oak–Hickory	69.2	93.9	411.4	103.2	107.1	347.3	221.3	94.8	316.6	105.8	246.8	151.3
Oak–Gum–Cypress	21.2	28.8	126.1	45.6	47.3	153.4	97.8	41.9	139.9	46.7	109.0	66.8
Other	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nonstocked	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	208.9	283.4	1241.7	350.4	363.6	1179.3	751.4	322.0	1074.9	359.2	838.1	513.7

Total area (1000 ha) of forest land converted from non-forest use of cropland, pasture, and developed use, by forest type.

3.4. Soil C estimates

We multiplied the mineral soil C estimates by area change. Over the 44-year period from 1953 to 1997, we estimated that the soil C accrued due to afforestation was 45.4 Tg C, about 1 Tg C/year on average. In terms of deforestation, about 126 Tg C was emitted over the time period, about 2.9 Tg C/year on average. These estimates only include the amount of mineral soil C that represented a real gain or loss. When area is deforested, that area is no longer considered forest and the mineral soil C of the entire area may not be counted. After all, the area no longer meets the criteria for forest. The amount of mineral soil C transferred from forest land because of deforestation from 1945 to 1997 was estimated to be 705 Tg C; while afforestation caused a transfer of 433 Tg C into the mineral soil forest C pool.

4. Discussion

The methodology provided a straightforward way to estimate forest soil C. We estimated that afforestation added very little to mineral soil C sequestration in forests of the southeastern region of the United States. Deforestation was estimated to emit more C over this period than afforestation sequestered. Land use change estimates may also be presented to indicate how much soil carbon is being transferred to and from areas that are considered forest. We estimated the amount of soil C being exchanged between categories of land use is five to 10 times larger that which is being sequestered from or emitted to the atmosphere. When interpreting soil C changes due to land use change, it is important to understand that the changes may be a transfer that should be reflected in the pool to which the area is being assigned.

More well-designed studies are needed on soil C pool and flux. There is little information on soil C changes due to land use change from forest to pasture, and, more importantly in the United States, due to land use change from forest to urban and other developed uses. High quality historical land use change data are also needed. This study is based on survey data beginning in 1953, which means we are not accounting for soil C on the large area of land converted to forest in this region earlier in the century, on which C continues to accrue. For future work, we suggest using historical land use change data for a period of approximately 100 years.

Acknowledgements

The USDA Forest Service, Northern Global Change Program, supported this work. We thank Louis Iverson, USDA Forest Service, Delaware, OH for the GIS work with STATSGO, and three reviewers for their excellent comments. This paper was presented at the USDA Forest Service Southern Global Change Program sponsored Advances in Terrestrial Ecosystem: Carbon Inventory, Measurements, and Monitoring Conference held 3–5 October 2000 in Raleigh, North Carolina.

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