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SOIL CHANGE AND CARBON STORAGE IN LONGLEAF PINE STANDS PLANTED ON MARGINAL AGRICULTURAL LANDS

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Abstract. An increasing area of marginal agricultural land in the coastal plain of the southeastern United States is being planted to longleaf pine (*Pinus palustris* Mill.). This chronosequence study in southern Georgia evaluated the effect of pine planting and the associated cessation of agricultural activity such as tillage and fertilization on soil C storage and soil nutrient stocks. Soils are Arenic or Typic Kandiudults with coarse-textured surface soils. Soil C, nutrients, and bulk density from 0 to 50 cm in planted stands 1, 3, 7, and 14 yr old, as well as soils beneath natural longleaf pine stands that were in a never tilled (NT) condition, were evaluated ($n = 3$ per stand age). No accumulation of soil C was apparent during the first 14 yr of pine growth. The average content of soil C in planted stands (11 ± 1 Mg/ha; mean ± 1 SE) was ~16 Mg/ha less than that in the NT soils (27 ± 4 Mg/ha). Soil total N content within planted stands also did not differ by age, although extractable NO_3 declined rapidly. Despite agricultural N inputs, the mean N content of planted stands (410 ± 83 Mg/ha) was below that in NT stands (730 ± 21 Mg/ha). Total P (1507 ± 21 Mg/ha) and extractable P (113 ± 21 Mg/ha) contents also did not differ between planted stands but had highly elevated values compared to total P (728 ± 38 Mg/ha) and extractable P (2 ± 1 Mg/ha) for NT soils. Soil exchangeable Ca, Mg, and K had generally decreasing contents with stand age but varying patterns related to NT soils. During the first 14 yr of reforestation, soils did not sequester C. Carbon benefits may be gained, however, in aboveground and belowground biomass accumulation and through the cessation of high energy-consumptive activities such as fertilization or tillage. Enhanced P fertility on these marginal lands can improve pine growth, but only if other elements such as N are not limiting to growth.

Key words: carbon storage; conservation reserve program; longleaf pine; marginal agricultural lands; soil cations; soil change; soil nitrogen; soil phosphorus.

INTRODUCTION

Longleaf pine (*Pinus palustris* Mill.) ecosystems covered a vast region of the southeastern United States coastal plain at the time of European settlement, circa 1600. Areal estimates range from 22×10^6 to 36×10^6 ha (Wahlenberg 1946, Ware et al. 1993). Currently $<0.5 \times 10^6$ ha are known to exist in this same region (Ware et al. 1993). To promote the reestablishment of longleaf pine in its native region the Conservation Reserve Program (CRP) has added additional credits for those farmers retiring marginal agricultural lands into longleaf pine (USDA 2000). The CRP program was originally designed to limit the over-production of certain crops and to provide environmental benefits such as reduced soil erosion and improved water quality. Currently, however, there has also been increased interest in using CRP lands as an offset for CO_2 emission, as per the Kyoto protocol (IPCC 2000). The regrowth of secondary forests on agricultural lands sequesters much C in aboveground woody biomass, whereas the sequestration of C as soil organic matter remains less certain (Richter et al. 1999, Post and Kwon 2000). On the recently reforested agricultural lands in this study, the potential for soil C storage may be enhanced due to the cessation of soil tillage. In addition, the residual effect of fertilizers added for agricultural crops may enhance biomass growth and thus increase C storage both above- and belowground.

In this study we evaluated changes in belowground soil C storage over 14 yr of longleaf pine regrowth within its native range in southern Georgia. We also assessed the change in soil nutrients after the cessation of fertilization in these agricultural fields. Further, we had the great advantage of having longleaf pine stands that exist on never tilled (NT) soils. These stands, which possess trees ranging up to 200 yr old, served as an end member for estimating the potential amount of previous C losses (or the future long-term potential for C gain) as well as providing a baseline for soil nutrient comparisons.

The objectives of this research were to (1) assess the

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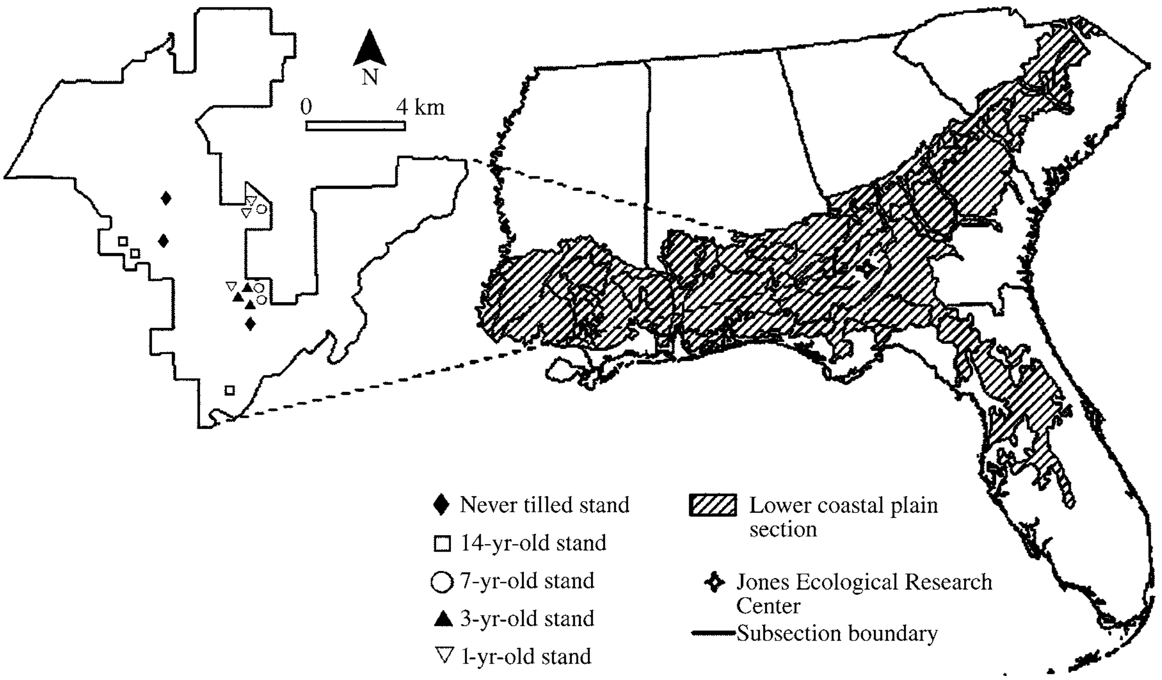

FIG. 1. Longleaf pine chronosequence stand locations on the Joseph W. Jones Ecological Research Center, Newton, Georgia.

potential for soil C sequestration in longleaf pine stands planted on marginal agricultural lands, and (2) assess the changes in soil nutrient status after the cessation of agricultural practices including fertilization and tillage.

METHODS

Research site

The Joseph W. Jones Ecological Research Center is located in the southwestern corner of Georgia within the Gulf of Mexico coastal plain, 31°19′ N and 80°20′ W (Fig. 1). The vegetation of this southeastern coastal plain region has been mapped as southern mixed forest and oak–hickory–pine forest, with smaller areas of southern floodplain forest and pocosins. The predominant vegetation form is evergreen needle-leaved trees with scattered areas of deciduous and evergreen broadleaved forest. Longleaf and slash (*Pinus elliotii* Engelm.) pines are prevalent throughout the region, while loblolly pine (*Pinus taeda* L.) is common in the northern areas (McNab and Avers 1994). Other classifications of the regional vegetation use the denomination of longleaf pine forest (Arnold 1978) or longleaf pine savanna (Frost et al. 1986, Bridges and Orzell 1989, Ware et al. 1993) to underline the historical importance of longleaf pine communities.

The Jones Center is a 12 500-ha tract of land mostly acquired in the mid 1930s by the late chairman of the Coca Cola Company, Robert Woodruff. Many of these lands were under longleaf pine savanna when they were acquired and are believed to have always existed in a forested state. Although some logging probably took place, many of these areas were never tilled or cultivated for agricultural crops. Much of the remaining area, however, was clearly under agriculture. Based on the oral history of the Center, these soils previously underwent many typical agricultural practices. In particular, the soils have been plowed, fertilized with N, P, and K, and planted to crops including cotton (*Gossypium* spp.) and sorghum (*Sorghum* spp.) (J. B. Actkinson, *personal communication*). Quantitative amounts of agricultural fertilizer inputs are unknown at these sites and soil erosion has likely been minimal due to the flat topography and coarse-textured soils of the Coastal Plain. This erosional history contrasts markedly with the Piedmont region of Georgia, which has undulating topography and fine-textured soil that suffered large losses. Regeneration of longleaf pine on these agricultural areas has taken place over the last two decades with establishment of plantations at a 2 × 3 m spacing, and 2–3 yr intervals of prescribed burning being an important part of the regeneration process (Wilson et al. 1999).

The climate of the Coastal Plain is humid subtropical. Mean daily temperatures are between 0°C and 18°C in the coldest month and >22°C in the warmest month; rainfall is distributed evenly throughout the year. Winter rainfall in this region is primarily a consequence of frontal cyclonic storms, whereas summer rain is usually associated with convectional thunderstorms. Mean annual temperature for this southwestern part of Georgia is 19.3°C and mean annual precipitation is 1370 mm (1958–2000, University of Georgia).[6]

The Jones Center is located in the Dougherty Plain physiographic province in the Gulf of Mexico Coastal Plain in southeastern United States. The Dougherty Plain has a sand and/or clay layer 3–39 m thick overlying highly fractured Ocala limestone with irregular pores perched on the relatively unfractured and dense Lisbon limestone. This region of the coastal plain is characterized by flat to gently rolling karst topography and has low topographic relief, with elevations ranging from 27 to 60 m above mean sea level. The greatest changes in elevation are found near permanent streams.

Soil collections

Replicate ($n = 3$) longleaf stands of varying ages (1, 3, 7, and 14 yr old plus the never tilled soil plots) were sampled in April 1999 (Fig. 1). The stands were similar in soil type, slope, and recent agricultural history. All soils were of the Wagram or Norfolk series, Arenic Kandiudults or Typic Kandiudults, respectively (USDA-SCS 1986). Both soils have an A or Ap horizon that can range from sand to sandy loam and a Bt horizon with yellow hue, 7.5 YR to 2.5 Y. The series differ in depth of the surface sand, with Norfolk being $<$50 cm (20 inches) and Wagram being $>$50 cm.

Soil O horizons were not sampled in this study because ground fires are prescribed on a 2-yr cycle, and thus the O horizon generally consisted of only 1 yr of pine needles and did not serve as a significant carbon or nutrient sink. Previous work of Binkley et al. (1992) in mixed loblolly–longleaf pine stands clearly demonstrated this effect of repeated fire on pine forest soil O horizons. Fine ash from previous burns was not prevalent on the soil surface, while charcoal pieces $>$2 mm were removed prior to analysis. The herbaceous layer was also relatively thin in the 1–14-yr-old plantations compared to the NT plots. In fact, the 1- and 14-yr-old stands were quite barren, likely due to recent abandonment in the age 1 stands and to a closed canopy in the age 14 stands. The age 3 and 7 stands did have competing vegetation, although here too percent ground cover was small compared to the NT plots. Agricultural activity has been shown to decrease herbaceous cover and diversity for pine ecosystems within the same region (Hedman et al. 2000).

Mineral soil samples were collected from each stand using a stainless steel probe (diameter 2.5 cm; length 60 cm) with removable internal liners and a slide hammer. Twenty soil cores per stand were sectioned into three different depths from the surface: 0–10, 10–20, and 20–50 cm and composited by depth and plot. Generally, we encountered an increase in clay content in the 20–50 cm horizon. Slopes were minimal in all plots, $<$2%.

Samples for physical and chemical analysis were returned to the laboratory, air dried, and passed through a 2-mm sieve prior to analysis. Soil total C and total N were measured after pulverization with a dry combustion technique using a Perkin-Elmer CNS analyzer (Perkin Elmer, Norwalk, Connecticut; Bremmer and Mulvaney 1982). Total P was measured on an Alpkem auto-analyzer (OI Analytical, College Station, Texas) using the Murphy-Riley chemistry after digestion with H_2SO_4–H_2O_2 and H_2SeO_2 as a catalyst (Kuo 1996). Extractable P was estimated using the double-acid (H_2SO_4–HCl) extract (Kuo 1996). NO_3 and NH_4 were measured on a Lachat auto-analyzer (Milwaukee, Wisconsin) (Lachat Instruments 1997) using the cadmium reduction method and the indophenol-blue method, respectively, after extraction in 1 mol/L KCl (Mulvaney 1996). Potassium, Ca, and Mg were measured by atomic absorption in the presence of $LaCl_3$ after extraction with double acid (Sumner and Miller 1996). Soil pH in water and 1 mol/L KCl was determined using a 1:2 mass : volume ratio (Thomas 1996). The cation exchange capacity (CEC) was determined using NH_4 exchange (Sumner and Miller 1996). Soil particle size analysis was determined using the hydrometer method on a composite sample for each age and depth to provide descriptive information (Gee and Bauder 1986).

Samples to estimate bulk density were collected in November 1999. A 7.5 cm diameter by 7.5 cm high brass core was collected from three locations within each plot within the 0–10, 10–20, and 30–40 cm depths ($n = 135$). The 30–40 cm core was used to estimate the bulk density of the 20–50 cm layer. Samples were returned to the laboratory, dried at 105°C for 48 h, and weighed.

Statistical analyses were most concerned with soil differences among plot ages, and a completely randomized design was selected in this experiment. Initially we conducted a one-way MANOVA test considering Wilks' lambda and Bartlett's approximation by each depth to test for an overall age effect. High colinearity between the soil variables can cause the determinant of the within-treatments sums of squares and cross-product matrix to be zero, making Wilks' test inapplicable (Johnson and Wichern 1998). To avoid this problem we excluded CEC, pHw, and bulk density from the initial analysis. If the test in step one was significant ($P < 0.05$), we conducted an F test (ANOVA with Fixed Effects Model) for all variables by depth with age as the treatment. If the univariate analysis was significant ($P < 0.05$), we then conducted Fisher's protected LSD ($P < 0.05$) to test the following orthogonal contrasts: never tilled (NT) vs. plantations, young plantations (1- and 3-yr-old) vs. old plantations (7- and 14-yr-old), 1-yr-old vs. 3-yr-old, and 7-yr-old vs. 14-yr-old. A contrast for linearity within age was tested as well (Dean and Voss 1999). Inferences from the chronosequence were often based on the observed trend in the first 14 yr of forest development, but orthogonal contrasts included the NT stands. We believe this ap-

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[6] URL: ⟨http://www.griffin.peachnet.edu/bae/⟩

proach to be more appropriate, since we do not know the true age of the NT stands. The soils within reforested stands also do not have the same initial conditions as the NT stands, and the pedogenic ages of the NT soils are unknown. Thus we want to be cautious in extrapolating the 1–14 yr age trend to the NT end point over an assumed period such as tree age, i.e., 200 yr.

RESULTS

The multivariate analysis using the Bartlett approximation of the Wilks' lambda statistic indicates that age (including the NT plots) is a significant factor affecting the soil parameters within each depth. Based on this result we used the univariate analysis and the orthogonal contrasts to interpret results for the individual soil parameters.

Bulk density

Soil bulk density decreased regularly with age of the stands (Table 1). In the 0–10 cm depth, bulk density decreased from 1.7 ± 0.07 to 1.2 ± 0.04 g/cm^3 (mean ± 1 SE), in the youngest and NT stands, respectively. This decrease is significant from the young stands to the old stands and from the reforesting plantations to the never tilled condition. In the 10–20 and 20–50 cm depth similar trends were observed (Table 1). Soil particle size distribution did not change much despite changing bulk density (Table 1).

C, N, and P

There was no clear trend in soil organic C or N with stand age. The concentration of total soil C in the NT stands (2.19 ± 0.19%), however, was significantly higher ($P < 0.05$) compared to the re-foresting stands (~0.6 ± 0.06%) in the surface 0–10 cm layer (Table 1). Like soil organic C, N concentration in the surface soil of the NT plots (0.06 ± 0.001%) was significantly higher as compared to the mean value of the reforesting plots (~0.025 ± 0.007%), Table 1. Total soil P had a contrasting pattern to that of C and N, as the NT stands had lower total soil P in 0–10 cm (112 ± 8 μg/g) than the reforesting stands (~221 ± 13 μg/g). In the NT plots, total soil P was lower at all depths when compared to the reforesting stands (Table 1).

In contrast to total N, extractable NO_3 was highest at all depths within the 1-yr-old stands as opposed to the NT stands (Table 1). These high concentrations of NO_3 in the 1-yr-old stands disappeared rapidly, however, such that the 3-yr-old stands had significantly lower NO_3, while the 7- and 14-yr-old stands had no significant difference in NO_3 concentration (Table 1). There was no difference in exchangeable NH_4 among any of the stand ages (Table 1).

Extractable P was similar to NO_3 in that the NT soils had the lowest concentrations of all stands at all depths (Table 1). Unlike NO_3, however, there was no significant difference in extractable P among the recently planted longleaf stands. In all of these stands extractable P in the upper 20 cm ranged from 15 to 30 μg/g. Even in the 20–50 cm layer, average extractable P in the recently planted stands (6.5 ± 1.4 μg/g) exceeded that in the NT soil by ~20-fold.

pH, cations, and exchange chemistry

In the 0–10 cm layer, there was no consistent trend in pHw and pHs since the 1-yr-old stand actually had a lower pH than the 3-yr-old stand. There is a decrease in pHw and pHs, however, from the 3-yr-old stands to the NT stands, and the NT stands do differ significantly from the reforesting stands (Table 2). The pH patterns are similar in the 10–20 cm layer, but in the 20–50 cm layer no significant differences among ages were found (Table 2). Patterns of pHs and pHw with depth differed between the soils of the young plantations and the NT stands. In the recently reforested soils pH is highest in the surface layer and decreases with depth, while the NT soils are most acidic on the surface but pH increases with depth (Table 2).

Soil exchangeable Ca and Mg shared similar temporal characteristics. For both elements there is a generally decreasing concentration from age 1 to 14 for all depths with some minor exceptions (Table 2). For example, 0–10 cm exchangeable Ca did not differ statistically between age 1 and 3. Compared to 14-yr-old stands, however, NT soils always had increased Ca and Mg concentrations, although again not all differences were statistically significant, i.e., Ca in the 20–50 cm layer. Exchangeable Ca and Mg concentrations decreased with depth except in the youngest stands where concentrations were quite similar in all depths (Table 2).

In contrast to Ca and Mg, exchangeable K concentrations at all depths were always greatest in the 1-yr-old stand and lowest in the NT soil condition (Table 2). In all depths there was a significant ($P < 0.05$) decrease in exchangeable K from the 1-yr-old to the 3-yr-old condition but not from the 7-yr-old to 14-yr-old condition. In the 0–10 cm depth, exchangeable K concentrations were similar among the 3, 7, 14, and NT stands, while in the 10–20 and 20–50 cm depths, exchangeable K decreased consistently from the youngest to NT stands. Exchangeable K did not have strongly decreasing trends with depth for any age forest stands.

Soil cation exchange capacity (CEC) (estimated by an NH_4 exchange method [Sumner and Miller 1996]) was elevated in the 0–10 cm layer of the NT stands compared to the plantations, a result consistent with the previous soil C data. Within the plantations and also at the deeper depths trends were not as consistent, although the older plantations had lower CEC than the younger plantations below 10 cm (Table 2).

DISCUSSION

The longleaf pine chronosequence on these marginal agricultural lands indicates that while some soil variables still maintain a clear agricultural legacy, others

TABLE 1. Soil bulk density and C, N, and P chemical parameters (April 1999) for a longleaf pine chronosequence in the upper coastal plain of southwestern Georgia (mean ± 1 SE).

Soil depth (cm)	Stand age (yr)	Bulk density (g/cm^3)	Sand (g/kg)	Clay (g/kg)	Total C† (%)	Total N (%)	Total P‡ (μg/g)
0–10	1	1.69 ± 0.07	836	50	0.69 ± 0.05	0.030 ± 0.006	215 ± 10
	3	1.61 ± 0.02	836	50	0.68 ± 0.03	0.023 ± 0.003	219 ± 9
	7	1.53 ± 0.02	836	60	0.74 ± 0.08	0.020 ± 0.011	216 ± 25
	14	1.50 ± 0.01	848	60	0.75 ± 0.08	0.030 ± 0.006	236 ± 6
	NT	1.22 ± 0.04	782	40	2.19 ± 0.18	0.060 ± 0.006	112 ± 8
Significant contrasts‖		A, B, E			A, E	A, E	A, E
10–20	1	1.81 ± 0.02	826	60	0.53 ± 0.13	0.013 ± 0.003	209 ± 8
	3	1.71 ± 0.01	836	40	0.49 ± 0.05	0.017 ± 0.003	218 ± 26
	7	1.67 ± 0.02	834	60	0.54 ± 0.06	0.013 ± 0.003	202 ± 22
	14	1.60 ± 0.07	832	60	0.54 ± 0.02	0.017 ± 0.003	201 ± 8
	NT	1.46 ± 0.04	776	70	0.91 ± 0.06	0.023 ± 0.003	97 ± 7
Significant contrasts‖		A, B, d, E			A, E	A, e	A, E
20–50	1	1.76 ± 0.03	756	90	0.26 ± 0.02	0.003 ± 0.003	166 ± 3
	3	1.71 ± 0.01	766	56	0.32 ± 0.08	0.003 ± 0.003	160 ± 18
	7	1.69 ± 0.01	790	80	0.34 ± 0.03	0.013 ± 0.008	162 ± 21
	14	1.56 ± 0.01	820	70	0.28 ± 0.03	0.003 ± 0.003	149 ± 9
	NT	1.54 ± 0.02	738	80	0.44 ± 0.06	0.013 ± 0.003	97 ± 6
Significant contrasts‖		A, B, C, d, E			A, E		A, E

Note: Stands of known age were originally planted on marginal agricultural lands, while NT is a natural stand on a never tilled soil.

† Soil total C and N were determined by dry combustion and pulverization.

‡ Soil total P was determined colorimetrically after digestion with H_2SO_4–H_2O_2.

§ Extractable NO_3 and NH_4 and extractable P were determined spectrophotometrically after extraction with 1 mol/L KCl or double acid, respectively.

‖ Within each depth, letters beneath a column indicate significance at $P < 0.05$ (capitals) or 0.10 (lowercase) for orthogonal contrasts: (A) never tilled (NT) vs. plantations; (B) young plantations (1- and 3-yr-old) vs. old plantations (7- and 14-yr-old); (C) 7-yr-old vs. 14-yr-old; (D) 1-yr-old vs. 3-yr-old; and (E) a contrast for linearity within age.

are rapidly approaching the never tilled (NT) condition. This contrast in the 0–10 cm soil variables is highlighted in the dendrograms resulting from a cluster analysis (Fig. 2). The cluster analysis clearly indicates that for the components CEC, total C, N, and P, and extractable P, the longleaf pine plantings all cluster as a group distinct from the NT soils. Conversely, for bulk density, extractable NO_3 and K, and soil pH, the older the longleaf pine planting the more similar is the variable to the NT soils. Among these variables in the 0–10 cm layer, some components are highly correlated to each other. For example, extractable NO_3 and exchangeable K are highly correlated ($r = 0.60$, for a linear Pearson correlation coefficient), as are total C and N ($r = 0.77$). The effects of agricultural activity on these soils are apparent, although reduced as soil depth increases.

The effect of agricultural activity on bulk density during conversion of forest is often rapid. Typically, the use of heavy equipment or cattle grazing will increase the bulk density of surface soils (Gracen and Sands 1980). The effect of reforestation on soil bulk density has been less well studied. The observed patterns in bulk density for this chronosequence are quite dramatic (Table 1). Not only have surface soils decreased significantly in bulk density during the first 14 yr of plantation growth, but bulk density decreases have also been observed through the upper 50 cm. Further, it is only in the highly organic matter enriched 0–10 cm layer that the NT soils are still substantially less dense than soil from the 14-yr-old plantations. These decreases in soil bulk densities after the cessation of heavy equipment use must be a function of forest processes such as tree root growth or bioturbation that can change soil structure and porosity (Johnson 1990, Graham and Wood 1991, Patton et al. 1995:33–67).

These changes in bulk density during forest growth require careful consideration when comparing soil chemical contents through time (Davidson and Ackerman 1993, Veldkamp 1994). The use of generic soil layers for interage plantation comparison contains an implicit assumption that the soil mass is static through time. The observed changes in bulk density, however, indicate that this assumption may not hold. In the current study, we have no knowledge of an appropriate reference such as the soil surface or maybe an argillic horizon from which to correct soil layer thickness. Further, since in this case all sampled layers have bulk densities that are changing simultaneously, the problem is further compounded. Due to these difficulties we have not made any correction to soil layer thickness in estimating soil contents. The magnitude of potential errors should be proportional to the observed changes in bulk density, and thus can approach 40% in the surface layer and 12% in the 20–50 cm layer. In the current situation of decreasing bulk density through time this will lead to possible overestimates of element loss, but conservative estimates of element accumulations.

The accumulation of soil C is of particular interest currently in regard to the Kyoto protocol for controlling

TABLE 1. Extended.

NO$_3$-N§ (μg/g)	NH$_4$-N§ (μg/g)	PO$_4$-P§ (μg/g)
0.76 ± 0.15	1.31 ± 0.09	24.0 ± 3.4
0.19 ± 0.16	1.23 ± 0.20	30.0 ± 4.5
0.05 ± 0.03	1.51 ± 0.26	22.9 ± 2.5
0.02 ± 0.01	1.33 ± 0.17	29.7 ± 3.3
0.01 ± 0.01	1.33 ± 0.14	1.7 ± 0.4
A, B, D, E		A, E
0.32 ± 0.07	1.10 ± 0.24	21.7 ± 0.8
0.07 ± 0.01	1.28 ± 0.11	27.8 ± 5.6
0.05 ± 0.07	1.17 ± 0.11	16.0 ± 3.5
0.01 ± 0.06	1.15 ± 0.12	21.2 ± 2.0
0.00 ± 0.00	1.25 ± 0.08	1.0 ± 0.6
A, B, D, E		A, E
0.20 ± 0.03	1.87 ± 0.83	5.0 ± 1.0
0.06 ± 0.01	0.93 ± 0.10	10.6 ± 3.3
0.02 ± 0.01	0.78 ± 0.10	4.5 ± 1.4
0.01 ± 0.01	0.89 ± 0.21	5.8 ± 1.0
0.03 ± 0.02	0.88 ± 0.05	0.3 ± 0.0
A, B, D, E		A, D, E

increasing greenhouse gases and with regard to the potential use of CRP lands as a source of C credits. During 14 yr of forest regrowth on these upper coastal plain soils of Georgia no increase in soil C content was measured (Fig. 3). Other studies of soil C accumulation during forest regrowth after agricultural use have provided varying results as recently reviewed by Post and Kwon (2000). In their review of 46 studies, soil C increased an average of 338 $kg \cdot ha^{-1} \cdot yr^{-1}$, but ranged broadly from −515 to +709 $kg \cdot ha^{-1} \cdot yr^{-1}$. The study locations ranged from cool temperate to tropical, and forest ages ranged from 8 to >250 yr old. The soils of the upper coastal plain are frequently of coarse texture surficially, which may limit the C sequestration potential (Richter et al. 1999). Further, in these longleaf pine plantations in particular, prescribed burning of the forest floor is practiced at regular intervals that may also limit the potential for soil C sequestration. A study in mixed loblolly–longleaf pine stands in the South Carolina coastal plain, however, with 30 yr of prescribed fire at 1-, 2-, 3-, and 4-yr intervals found no effect on mineral soil C compared to controls (Binkley et al. 1992). Finally, it is possible that 14 yr is simply an insufficient period in which to measure changes in soil C.

Although no change in soil C content was apparent among plantations, a clear difference existed between the plantations and the NT soils. In comparison to the surface soil C content of NT soils (26.7 ± 2.2 Mg/ha), the average of the plantation soils (11.2 ± 0.3 Mg/ha) was ∼15 Mg/ha lower (Fig. 3). This difference in soil C is likely to approximate the C lost as a result of forest clearing for agriculture during the previous century of land use. A similar quantity of soil C loss (13 Mg/ha for 0–15 cm soil) was found in the piedmont of South Carolina when comparing soils from pine plantations regrown on old agricultural fields to soils from hardwood stands that were in a never tilled condition (Richter et al. 1995, Richter and Markewitz 2001). On a percentage basis, however, this speculated soil C loss of 56% (i.e., 15 of 26.7 Mg/ha) is high compared to the average of 40% found in a review by Davidson and Ackerman (1993) of C loss following cultivation of previously untilled soils. Regardless, this soil C loss may provide the best estimate of the long-term, i.e., 100-yr, potential for sequestration of soil C on marginal agricultural lands in the southern coastal plain under replanted pine forests.

In addition to the potential sequestration of C in soils on these marginal agricultural lands, it should be recognized that some C benefit will be derived from the accumulation of C in aboveground biomass. Net primary productivity (NPP) on intermediate-site potential longleaf pine savanna can approach 6 $Mg \cdot ha^{-1} \cdot yr^{-1}$ (Mitchell et al. 1999). Also, the absence of agricultural activity will provide C benefits due to the energy savings from the cessation of fertilizer use, herbicide use, or the passage of equipment on the site (Schlesinger 2000). Thus the absence of soil C sequestration alone should not be misinterpreted to indicate that no C benefits will be derived from retiring marginal agricultural lands.

The patterns in total N contents were similar to those of total C with no change in surface soil (0–10 cm) N content apparent during the 14 yr of plantation growth. The mean N content in the surface soil among the four different-aged plantations was 410 ± 48 kg/ha (mean ± 1 SE) compared to 730 ± 21 kg/ha within the three NT stands (Fig. 3). It is somewhat surprising that despite 14 yr of tree growth, no depletion of the soil N pool is apparent among the plantations. In the 28-yr-old loblolly pine plantation of Richter and Markewitz (2001), soil N pools (0–60 cm) were depleted by ∼900 kg/ha, and much of this soil removal could be accounted for by uptake into plant biomass and forest floor. Similarly, after 32 mo of eucalyptus growth in Hawaii, Binkley and Resh (1999) found depletions of soil N (190 kg/ha) despite having input 700 kg/ha of fertilizer N, although in this case plant uptake alone could not account for all N depletions. We did not measure aboveground biomass contents in this study, but we would expect >200 kg/ha of N in pine biomass by age 14 (Albaugh et al. 1998). Nitrogen-fixing species such as *Desmodium ciliare* Muhl. Ex Willd., *Galactia microphylla* Chapm., *Galactia volubilis* L., or *Tephorosia florida* Dietr. are present in the mature longleaf ecosystems (Goebel et al. 1997) and may well be present in the regrowing forest stands, although at low densities. Research in managed pine ecosystems of the Piedmont of Georgia indicated that regular understory burning can increase the frequency and density of herbaceous legumes potentially enhancing N inputs (Hendricks and Boring 1999).

Beyond the lack of N depletion during the first 14 yr of pine growth, it is also somewhat surprising that

TABLE 2. Soil pH and exchangeable cation parameters (April 1999) for a longleaf pine chronosequence in the upper coastal plain of southwestern Georgia (mean ± 1 SE).

Soil depth (cm)	Stand age (yr)	pHw†	pHs†	Ca‡	Mg
0–10	1	5.40 ± 0.16	4.46 ± 0.14	0.352 ± 0.042	0.080 ± 0.005
	3	5.74 ± 0.08	4.80 ± 0.10	0.622 ± 0.186	0.066 ± 0.012
	7	5.67 ± 0.16	4.68 ± 0.22	0.345 ± 0.076	0.067 ± 0.013
	14	5.16 ± 0.18	4.15 ± 0.17	0.172 ± 0.047	0.040 ± 0.016
	NT	5.04 ± 0.08	4.04 ± 0.06	0.565 ± 0.204	0.108 ± 0.023
Significant contrasts‖		A, C, E	A, C, E		A
10–20	1	5.19 ± 0.25	4.26 ± 0.21	0.340 ± 0.055	0.064 ± 0.010
	3	5.64 ± 0.07	4.75 ± 0.05	0.414 ± 0.009	0.071 ± 0.010
	7	5.35 ± 0.23	4.43 ± 0.27	0.267 ± 0.051	0.055 ± 0.009
	14	4.83 ± 0.14	4.02 ± 0.08	0.097 ± 0.046	0.020 ± 0.009
	NT	5.18 ± 0.04	4.22 ± 0.03	0.222 ± 0.050	0.062 ± 0.008
Significant contrasts‖		b, c, d	D	B, C, e	B, C, e
20–50	1	4.95 ± 0.14	4.04 ± 0.12	0.347 ± 0.082	0.068 ± 0.018
	3	5.20 ± 0.08	4.23 ± 0.05	0.278 ± 0.043	0.048 ± 0.005
	7	5.11 ± 0.19	4.15 ± 0.15	0.198 ± 0.026	0.046 ± 0.013
	14	4.85 ± 0.23	4.10 ± 0.06	0.107 ± 0.065	0.017 ± 0.007
	NT	5.25 ± 0.06	4.24 ± 0.04	0.192 ± 0.026	0.073 ± 0.011
Significant contrasts‖				B, E	A, B

Notes: Stands of known age were originally planted on marginal agricultural lands, while NT is a natural stand on a never tilled soil. Ca, Mg, K, Na, and CEC were measured in units of centimoles of charge per kilogram.

† Soil pHw is pH measured in 1:2 ratio of soil to deionized water, while pHs is pH measured in the same ratio using 1 mol/L KCl.

‡ Exchangeable cations were estimated with the double acid extract in a 1:10 mass : volume ratio.

§ CEC (cation exchange capacity) was estimated using an NH_4 exchange method.

‖ Within each depth, letters beneath a column indicate significance at $P < 0.05$ (capitals) or 0.10 (lowercase) for orthogonal contrasts: (A) never tilled (NT) vs. plantations; (B) young plantations (1- and 3-yr-old) vs. old plantations (7- and 14-yr-old); (C) 7-yr-old vs. 14-yr-old; (D) 1-yr-old vs. 3-yr-old; and (E) a contrast for linearity within age.

despite many years of fertilizer inputs to soils beneath the regrowing forest, e.g., 50 kg·ha^{-1}·yr^{-1} (although exact historical agricultural inputs are unknown), that a deficit of N is apparent in the surface soils compared to the NT stands. Again, N fixation may play an important role. In contrast to total N, however, extractable NO_3 was higher in the 1-yr-old stands compared to the NT stands, but this NO_3 was rapidly lost from the soils (Fig. 4). In addition, this amount of N as NO_3 was a relatively small content in the 0–50 cm layer, i.e., 2.9, 0.74, 0.28, 0.07, and 0.13 kg/ha for the 1, 3, 7, 14, and NT stands, respectively. The ~3 kg/ha difference between the 1-yr-old and NT stand represents only a small fraction of the N we would expect in tree uptake.

Unlike total C or N contents, the content of total P in plantation soils exceeds that in the NT soils, although differences among the plantation soils during the first 14 yr of growth were not apparent (Fig. 3). In the 0–10 cm layer the average total P content for all plantations was 350 ± 8 kg/ha compared to 136 ± 13 kg/ha for the three NT plots. For the 0–50 cm layer, total P contents were 1507 ± 50 and 729 ± 38 kg/ha for plantations and NT stands, respectively. Extractable P also showed an increase in the cultivated soils compared to the NT soils. In the 0–10 cm layer extractable P contents were 42 ± 3 kg/ha in the plantations compared to only 2.0 ± 0.4 kg/ha for the NT soils, while the similar comparison for the 0–50 cm layer was 113 ± 14 and 6 ± 2 kg/ha, respectively. A retention or persistence of P fertilizer input is a relatively common phenomenon in forest soils even well after agricultural abandonment (Fransson and Bergkvist 2000, Richter and Markewitz 2001). These increases in available P resulting from agricultural practices must improve soil fertility for tree growth, particularly in the southeastern United States coastal plain where soil P availability can often be limiting. In the absence of sufficient N (as possibly indicated above), however, increased fertility due to P might be of little practical value.

The patterns for cationic element (Ca, Mg, and K) contents differ from those of total C, N, or P. In the previous cases changes during forest growth were minimal (except for NO_3), but plantations differed from NT plots. In the case of the cationic elements all components have generally decreasing trends from age 1 to 14 in all soil layers (Table 2). The difference in contents (estimated from Tables 1 and 2) between age 1 and age 14 plantations for 0–50 cm are 889, 259, and 17 kg/ha for Ca, Mg, and K, respectively. Losses of base cations after agricultural abandonment and during reforestation have been previously observed (Richter et al. 1994). The mechanisms driving these cation depletions have been debated with respect to the role of acid deposition (Johnson et al. 1991, Markewitz et al. 1998) compared to biomass uptake, and in many cases have been influenced by previous land use history (Markewitz et al. 1998, Binkley and Resh 1999). In this study the difference in contents for Ca and Mg likely exceed amounts that can be accounted for by plant uptake, although this is not the case for K. Leach-

TABLE 2. Extended.

K	Na	CEC§
0.139 ± 0.016	0.003 ± 0.001	0.898 ± 0.054
0.067 ± 0.015	0.009 ± 0.008	0.836 ± 0.055
0.064 ± 0.002	0.003 ± 0.001	0.875 ± 0.081
0.080 ± 0.019	0.003 ± 0.000	0.552 ± 0.065
0.062 ± 0.014	0.013 ± 0.004	1.341 ± 0.346
B, D, E	A	A, C, E
0.088 ± 0.016	0.000 ± 0.000	0.869 ± 0.109
0.049 ± 0.002	0.003 ± 0.001	0.750 ± 0.028
0.046 ± 0.002	0.002 ± 0.001	0.711 ± 0.070
0.043 ± 0.006	0.000 ± 0.000	0.478 ± 0.042
0.029 ± 0.006	0.005 ± 0.001	0.773 ± 0.055
A, B, D, E	B, C, E	b, c, d
0.103 ± 0.014	0.000 ± 0.000	0.981 ± 0.114
0.053 ± 0.003	0.002 ± 0.001	0.641 ± 0.051
0.046 ± 0.005	0.001 ± 0.001	0.764 ± 0.032
0.035 ± 0.008	0.004 ± 0.001	0.478 ± 0.055
0.020 ± 0.006	0.006 ± 0.001	0.652 ± 0.029
	A, B, D, E	B, C, D, E

ing losses of divalent cations, however, are probably high shortly after agricultural abandonment since exchange capacity can be more base saturated due to liming practices (Richter et al. 1992, Markewitz et al. 1998, Binkley and Resh 1999).

In comparison to the generally decreasing trend observed for cations from age 1 to 14, NT plots have cation contents higher than 14-yr-old stands. Exchange chemistry differs in NT surface soils, however, in that CEC is elevated by 2–3 fold while base saturation is lower (Table 2). The higher CEC in these surface soils must derive partly from the higher C contents, but the lower pH in these soils decreases the quantity of negative variable charge generated by the soil organic matter. The variable trends for CEC through the chronosequence probably reflect an interaction of CEC with changes in soil pH and soil C content (Tables 1 and 2).

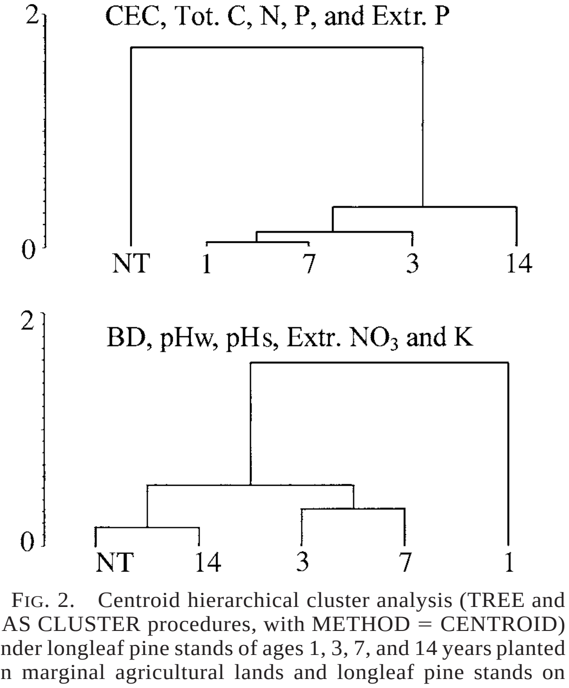

FIG. 2. Centroid hierarchical cluster analysis (TREE and SAS CLUSTER procedures, with METHOD = CENTROID) under longleaf pine stands of ages 1, 3, 7, and 14 years planted on marginal agricultural lands and longleaf pine stands on never tilled (NT) soils. Soil parameters were analyzed in 1999 within the 0–10 cm layer. Normalized centroid distance is represented on the vertical axis (i.e., the distance between two clusters is the squared Euclidean distance between their centroids or means). CEC is cation exchange capacity; Tot. is total; Extr. is extractable; BD is bulk density; pHw is soil pH in water; pHs is soil pH in 1 mol/L KCl.

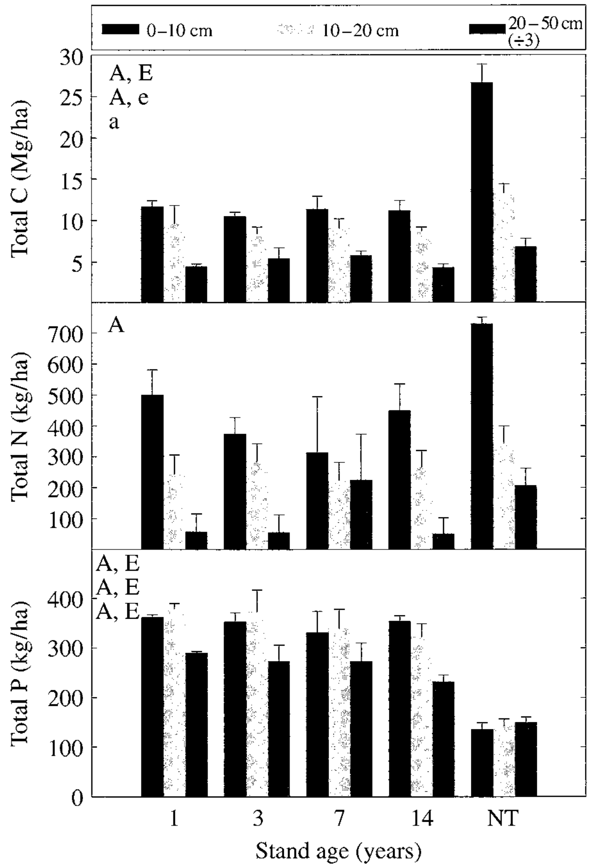

FIG. 3. Soil contents of C, N, and P for soil in a longleaf pine chronosequence in the Joseph W. Jones Ecological Research Center, Newton, Georgia (mean + SE). Samples were collected in April 1999. Letters indicate significance at $P < 0.05$ (capitals) or 0.10 (lowercase) for orthogonal contrasts: (A) never tilled (NT) vs. plantations; (B) young plantations (1- and 3-yr-old) vs. old plantations (7- and 14-yr-old); (C) 7-yr-old vs. 14-yr-old; (D) 1-yr-old vs. 3-yr-old; and (E) a contrast for linearity within age. Contrasts not shown were not significant.

Soils such as those described above, which are within marginal agricultural lands, are clearly responding to the conversion from agriculture to a pine forest ecosystem. In 1998, of the 2.025 × 10^6 hectares in the CRP program, ~41 310 ha of longleaf pine plantings were accepted across nine southern states, with approximately 30 375 ha of this area being planted in

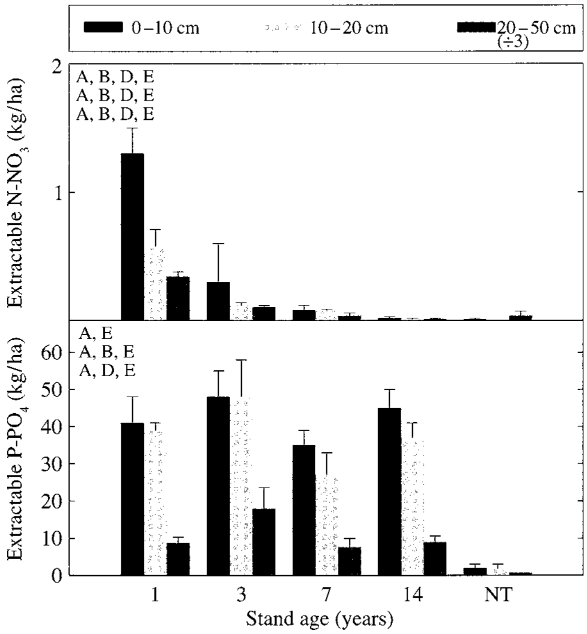

FIG. 4. Soil contents of extractable NO$_3$-N and PO$_4$-P for soil in a longleaf pine chronosequence in the Joseph W. Jones Ecological Research Center, Newton, Georgia (mean + 1 SE). Samples were collected in April 1999. Letters indicate significance at $P < 0.05$ (capitals) or 0.10 (lowercase) for orthogonal contrasts: (A) never tilled (NT) vs. plantations; (B) young plantations (1- and 3-yr-old) vs. old plantations (7- and 14-yr-old); (C) 7-yr-old vs. 14-yr-old; (D) 1-yr-old vs. 3-yr-old; and (E) a contrast for linearity within age. Contrasts not shown were not significant.

Georgia (USDA 1998). The soils within these reserve program lands are providing certain environmental benefits. For example, soil erosion has probably diminished due to tree cover, and any NO$_3$ leaching from these soils that could affect water quality has likely ceased. Benefits gained through the sequestration of C as soil organic matter is probably small, at least during the first decade of tree growth. If, however, an NT soil condition was regained on all 41 310 ha, an accumulation of up to 1.5 Tg (teragrams) of C is possible, although the time frame for such an occurrence is unknown and the probability is low.

CONCLUSIONS

The results of this study indicate that during the first 14 yr of reforestation on marginal agricultural lands with longleaf pine, soils will likely not sequester large quantities of C. This is not to suggest that no C will be sequestered by the ecosystem, since relatively large quantities can accumulate in aboveground and belowground (root) biomass. Further, additional C benefits will be derived from energy savings gained by discontinuing the use of herbicides, pesticides, fertilizers, and heavy equipment on these lands. Further, over a longer time period soil C may begin to rebuild to levels observed in the never tilled condition.

A cessation of fertilization on these lands will also likely lead to a decrease of available N in the soil, although total amounts of N, particularly on an ecosystem basis, will probably not change dramatically. The high base saturation of these soils will also probably decrease over time as soils re-equilibrate to a more native condition, but over the short term (i.e., 5 yr) cation availability should be higher as elements are released to solution. Total amounts of cations may rebuild over the long term (through atmospheric inputs or deep root uptake) if soil organic matter is to reaccumulate and increase CEC. Finally, both available and total P will probably stay elevated on these lands for a number of decades. This increased P availability can be interpreted as an increase in site fertility, but may provide little benefit to tree growth if other elements are limiting to growth.

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