Soil & Tillage Research 47 (1998) 245–251

Management effects on C accumulation and loss in soils of the southern Appalachian Piedmont of Georgia

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Abstract

Soil conservation management practices can impact on soil C storage. Long- and short-term data sets from three research sites were used to assess effects of management on C content of soils on the southern Appalachian Piedmont of Georgia. Intensive cultivation resulted in no observable change in total C content at the end of 3 yr, but at the end of 16 yr there were 40% and 18% declines in C in conventional tillage (CT) and no-tillage (NT) soils, respectively, at the Horseshoe Bend site. No significant changes in soil C were observed in either CT or NT soils at the end of 16 yr at Griffin. Higher clay content of Griffin soils may have contributed to this difference. Newly established NT plots on C-depleted soils on Dawson Field showed no change in C content at the end of 3 yr on both a highly eroded Pacolet sandy clay loam and a slightly eroded Cecil sandy loam. A soil under long-term NT accumulated C at a mean rate of ca. 0.6 Mg C ha^{-1} yr^{-1}, reaching 29 Mg C ha^{-1} after 20 yr. Steady-state levels of C in soils of the region may approach 40 Mg C ha^{-1} (0–20 cm depth). Long-term forested and sod-based soils at Griffin showed C contents approximating this steady-state, while fertilized NT soils exceeded the estimated steady-state level. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Soil carbon; No-tillage; Long-term management

1. Introduction

Long-term tillage is known to reduce carbon concentrations in soil (Dalal and Mayer, 1986; Kern and Johnson, 1993) and, historically, has contributed to elevated CO_2 concentrations in the atmosphere (Coleman et al., 1984; Schlesinger, 1991). Conservation management practices (e.g., no-tillage, sod rotations, organic amendments) can increase carbon concentrations in degraded soils and are of interest not only to improve soil physical, chemical and biological characteristics, but also to provide a sink for atmospheric carbon. Sequestration of carbon in soil has been identified as an important goal for land management (Environmental Protection Agency, 1991; Council for Agricultural Science and Technology, 1992; Kern and Johnson, 1993; Dixon et al., 1994; Burke et al., 1995).

The few previous studies of organic matter dynamics in soils of the southern Appalachian Piedmont (USA) have shown rapid losses of soil organic matter (SOM) following conventional cultivation of soils converted from forest or sod (Giddens, 1957; Jones et al., 1966). More recent long-term studies at

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PII S0167-1987(98)00113-5

our research sites have shown that SOM concentrations can be increased or that losses can be reduced under conservation management (Hargrove et al., 1982; Bruce et al., 1995; Bruce and Langdale, 1997; Hendrix, 1997). However, these patterns appear to vary with soil texture, landscape position and management practices. This paper explores the potential for soils in the southern Piedmont region to sequester carbon under various management regimes. We based our assessment on long-term data bases and short-term field experiments from three research sites on the Piedmont of Georgia, USA, representing a range of management histories, soil types and landscape positions. Our objective was to evaluate short- and long-term responses of soil carbon to different management practices.

2. Materials and methods

2.1. Site descriptions

The southern Appalachian Piedmont region of the southeastern US extends from eastern Maryland southwest into central Alabama, and consists of diverse landscapes of urban, forest, pasture and row crop land uses. Climatic regimes fall between warm, moist-temperate and subtropical (Post et al., 1985; Bailey, 1989). Trimble (1974) and Little (1987) give detailed accounts of the history of land use and soil degradation in the region.

The three areas used in this assessment were (1) the USDA-ARS Southern Piedmont Conservation Research Center, Watkinsville, GA; (2) the University of Georgia Agricultural Experiment Station, Griffin, GA; and (3) the Horseshoe Bend Agroecosystem Research Area, University of Georgia, Athens, GA. Annual rainfall and air temperature across these areas average approximately 1300 mm and 17°C, respectively.

Two sites were considered near Watkinsville, GA (33°54′N 83°24′W). The P-1 watershed is a 1.3 ha area that has been under no-tillage and double crop management [summer soybeans (*Glycine max* L. Merr.) or grain sorghum (*Sorghum bicolor* (L.) Merr.) and winter wheat (*Triticum* sp.) or crimson clover (*Trifolium incarnatum* L.)] since 1972. Prior to this, the site was severely eroded from intensive cultivation and had a C content of ca. 17 Mg ha^{-1} to 20 cm (Bruce and Langdale, 1997). Site history has been described in Smith et al. (1978) and Langdale et al. (1984). Soils in the watershed are in the Madison, Cecil and Pacolet series (clayey, kaolinitic, thermic, Typic Kanhapludults) on slight to moderate slopes. Dawson Field was a 20 ha area that had been under intermittent fallow, pasture and conventional row crop cultivation for over 100 yr and, at the beginning of the study, was characterized by low organic carbon content (14–23 Mg C ha^{-1} to 20 cm depth) and various soil textures resulting from erosion. Soils included toposequences of Cecil and Pacolet soils of slight to severe erosion status. In 1988 a series of management treatments, including no-tillage (NT) and double-cropping with summer grain sorghum and winter wheat, were established on a 1.8 ha area on the west side of the field and studied for changes in soil C. Both P-1 watershed and Dawson Field represent upland Piedmont sites.

A series of long-term conventional tillage (CT-moldboard plowed to 15 cm followed by disking) and NT (direct-drilled without plowing) plots were studied at Bledsoe Research Farm near Griffin, GA (33°10′N 84°20′W). The plots were established in 1975 on a site that had been in tall fescue [*Festuca arundinacea* (Schreb.) Wimm] sod for an undetermined number of years (Hargrove et al., 1982). The site is on an upland of predominantly Cecil sandy loam soil (clayey, kaolinitic, thermic, Typic Kanhapludult). The plots were double-cropped with summer soybeans or grain sorghum followed by winter wheat, rye (*Secale cereale* L.) or crimson clover during the study. The Griffin study also included long-term fescue sod and pine (*Pinus* sp.) forest areas.

Another series of long-term CT (moldboard plowed to 15 cm followed by disking and rotory tillage) and NT (direct-drilled without plowing) plots were sampled at the Horseshoe Bend site in Athens, GA (33°56′N 83°22′W). These plots were established in 1978 on a 0.8 ha bottomland terrace of a river floodplain on Hiwassee series soil (fine loamy, siliceous, thermic, Rhodic Kanhapludult). The site had most recently been in old field for 10 yr and previously in millet (*Setaria* sp.) or forage grasses for an unknown period of time (since at least 1938). Cropping systems since 1978 have consisted of double cropping with summer grain sorghum, soybeans or corn (*Zea mays* L.) followed by winter rye (Stinner et al., 1984; Groffman et al., 1986; Beare et al., 1992; Hendrix, 1997). A long-term, mixed grass meadow was also sampled at Horseshoe Bend.

In 1989, a series of small (2 m^2) plots was established in organic-C-enriched grass sods at Griffin and Horseshoe Bend to assess short-term changes in soil C. Three treatments (four replicates each) were applied to these plots: CT (intensive rotary cultivation twice yearly and cropping with summer grain sorghum), NT (direct drilling after killing the sod with glyphosate and cropping with summer grain sorghum and winter rye), and no management other than annual mowing of the sod [see Hendrix (1997) for detailed experimental design]. A similar set of small plots was established on Dawson Field to assess short-term changes in organic-C-depleted soils (Cecil and Pacolet) brought into NT management. In all of the short-term studies, soil samples were collected and analyzed twice yearly for total C, as described below.

2.2. Sampling and analyses

Soil samples for total C analysis were collected using 5.8 cm diam. cores. In the long-term studies, at Watkinsville, P-1 watershed was sampled in 1991 (19 yr after establishment of NT management) at 29 locations to a depth of ca. 1.5 m. Carbon data reported here are means from this sampling. Dawson Field was sampled twice yearly for 3 yr beginning in 1989 (1 yr after initiation of NT). Replicate samples (four bulked samples from each plot) were collected to 25 cm depth at four locations each on Cecil and Pacolet soils. Samples from P-1 watershed and Dawson Field were air dried, passed through a 2 mm sieve, ground to fine powder consistency in a Spex Mill, and analyzed in a Carlo Erba CN analyzer.

At the Griffin site, soil samples (four bulked samples from each plot) were collected to 30 cm depth beginning in 1980, 5 yr after the study was initiated, and at 1 to 5 yr intervals thereafter. All samples were air dried and passed through a 2 mm sieve. The first samples were analyzed for organic C with the Walkley-Black technique (Nelson and Sommers, 1982). From 1985 onward, C was determined in a LECO Carbon Determinator or a Carlo Erba CN Analyzer. Soils from Horseshoe Bend were first analyzed for C in 1982, 4 yr after establishment of the plots, and then every 2 to 3 yr. Samples (four bulked samples from each plot) were collected to 21 cm depth, air dried, passed through a 2 mm sieve, and then analyzed in a LECO Carbon Determinator, or ground in a Spex Mill and analyzed in a Carlo Erba CN Analyzer. Carbon content of soils prior to the start of the long-term studies at both Griffin and Horseshoe Bend was not measured. Initial C content of all short-term plots was measured in 1989.

Unless otherwise stated, soil C contents are given to a depth of 20 cm. Where sampling depth increments were other than 20 cm, C in the upper 20 cm was calculated from measured C and known or estimated bulk densities, assuming a depth distribution of C similar to that reported for two Cecil soils by Bruce and Langdale (1997). Their measurements showed that 42% of soil C standing stocks in these soils occurred in the upper 20 cm of the profile. This approach allowed for a comparison of literature and observational data on soil C content across a range of sites.

3. Results and discussion

3.1. Long-term patterns of C storage

Depletion of SOM following cultivation of native ecosystems has been observed world-wide (Jenny, 1980; Coleman et al., 1984; Dalal and Mayer, 1986; Mann, 1986; Kern and Johnson, 1993). Fig. 1 is a chronosequence constructed from historic data and represents changes in soil C concentration in response to management across a number of sites on the southern Appalachian Piedmont of Georgia. Giddens (1957) reported rapid declines in soil C concentrations (30% in 3 yr) following cultivation of virgin forest soils. Other studies suggest that after extended periods of cultivation, C concentrations in soils of this region approach 6–7 g C kg^{-1}, a decline of as much as 70% from initial levels (Giddens, 1957; Jones et al., 1966; Smith et al., 1978; Langdale et al., 1979, 1987; Bruce and Langdale, 1997). Similar rates of decline have been reported from tropical and subtropical ecosystems under cultivation (Dalal and Mayer, 1986; Detwiler, 1986; Lugo and Sanchez, 1986). The reciprocal process of SOM aggradation also occurs rapidly in Piedmont soils (Fig. 1) when C-depleted soils are converted to sod (Jones et al., 1966) or conservation

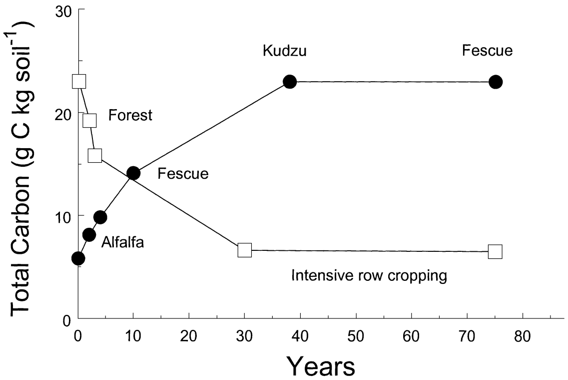

Fig. 1. Chronosequences of organic C concentrations in the plow layer (0–15 cm) of Georgia Piedmont soils at several sites under various management and vegetation for various lengths of time. Open symbols represent degradation of C following plowing of native forest soil and long-term, intensive row cropping. Closed symbols represent aggradation of C following conversion of degraded soils from row cropping to sod or kudzu [*Pueraria lobata* (Willd.) Ohwi]. The first three points in each sequence are actual observations over time at a given site; subsequent points are from different sites. Data from Giddens (1957) and Jones et al. (1966). Modified from Hendrix (1997).

management (Hargrove et al., 1982; Langdale et al., 1987; Bruce and Langdale, 1997). Similarly, data from Lugo and Sanchez (1986) and Fisher et al. (1994) suggest rapid increases in soil C during forest succession or following pasture establishment in degraded tropical soils.

Estimates of soil C content (which integrates C concentration and bulk density over the soil profile on an area basis) from ecosystems under a variety of long-term management regimes within the southern Piedmont are shown in Table 1. At the top of the table, the estimated values of soil C content in warm temperate to subtropical forests were converted to 20 cm depth from Post et al. (1985), assuming depth distributions and bulk densities similar to those reported by Bruce and Langdale (1997). This value (39 Mg C ha^{-1}) may approximate the upper limit for C storage in Piedmont ecosystems receiving organic matter inputs only from unsubsidized, native vegetation. Estimated values of C content in agricultural soils in the southern Piedmont are averages over the entire region presented by Kern and Johnson (1993) and were also converted to 20 cm assuming the C depth distributions and bulk densities of Bruce and Langdale (1997). The range of values (34–38 Mg C ha^{-1}) represents 3–13% reductions of C from the estimated upper limit of 39 Mg C ha^{-1}. In view of our observations of C content in agricultural soils (discussed below), the estimates by Kern and Johnson (1993) seem high for degraded soils with a long history of intensive cultivation, as occurred on the southern Appalachian Piedmont.

Observed C content of soils at our research sites ranged from a low value of 14 Mg C ha^{-1} in long-term, intensively cultivated Cecil soils on Dawson Field, to a high value of 48 Mg C ha^{-1} in long-term NT soils in Griffin. It is interesting that the latter exceeds the predicted equilibrium value for native ecosystems in the region, while the forest, sod and CT systems at Griffin approximate this value. These results may reflect the effects of fertilizers and other management subsidies which would be expected to increase Soil C in the NT agricultural systems compared to the native ecosystems. Results suggest high productivity, high organic input rates, and/or slower decomposition rates, in the NT systems. Horseshoe Bend soils ranged between 20 Mg C ha^{-1} in an unmanaged grass meadow to 28 Mg C ha^{-1} in long-

Table 1
Estimated and observed organic C content (to 20 cm) in Georgia Piedmont soils

	Mg C ha^{-1}	Reference
Estimations:		
Warm-temperate moist forest	39	Post et al. (1985)
Subtropical moist forest	39	Post et al. (1985)
Field cropland	34–38	Kern and Johnson (1993)
Observations:		
Griffin		
Forest (Cecil) [a]	38	This paper
Sod (Cecil)	40	This paper
NT (Cecil)	48	This paper
CT (Cecil)	38	This paper
Horseshoe Bend		
Sod (Hiwassee)	20	This paper
NT (Hiwassee)	28	This paper
CT (Hiwassee)	22	This paper
Dawson Field		
CT (Cecil)	14	This paper
CT (Pacolet)	21	This paper
P-1 Watershed		
NT (Cecil)	28	Bruce and Langdale (1997)

[a] Soil series.

term NT plots, all considerably below the predicted equilibrium. These observations may reflect lower productivity of the agricultural systems at Horseshoe Bend compared to those at Griffin, as well as lower capacity of the coarser textured soils at Horseshoe Bend to sequester organic C.

3.2. Experimental studies

Temporal changes in C content of soils from the long-term CT and NT plots at Griffin and Horseshoe Bend are shown in Figs. 2 and 3. At Griffin, there was no indication of a decrease in C content over 11 yr in either CT or NT plots (Fig. 2). Carbon may have increased somewhat in NT but the trend was not significant. Although C was not measured at the beginning of the study in 1975, nearby long-term fescue sod plots contained approximately 45 Mg C ha^{-1} (to 25 cm). If this value is representative of initial conditions in the tillage experiment, then there may have been little change in soil C over 16 yr of the study. In contrast, both CT and NT plots at Horseshoe Bend showed decreases in soil C over a 12 yr period; the declines were ca. 40% in CT and 18% in NT (Fig. 3). It is interesting that significant differences between CT treatments were not apparent until the 1994 sampling date. The amount and rate of change in C content in response to management depends on initial C content, soil texture, climatic conditions, organic inputs and other management factors which differed to some extent between Griffin and Horseshoe Bend. In particular, coarser texture and lower clay content of Horseshoe Bend soils may have contributed to the decline in soil C after conversion to agricultural management.

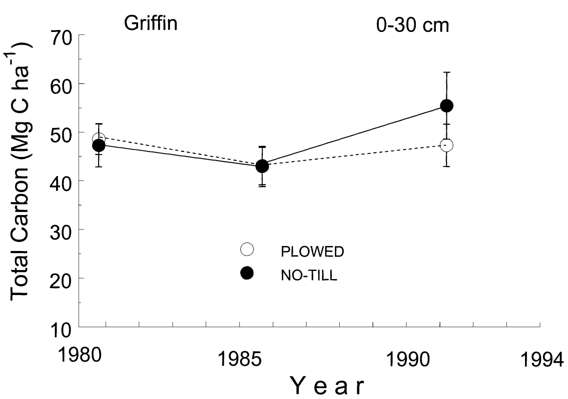

Fig. 2. Total C content in the soil profile to 30 cm over 11 yr in the long-term plowed and no-tillage plots at Griffin. Points represent means with standard error bars.

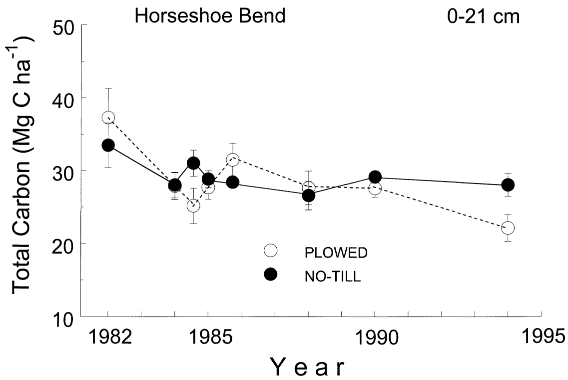

Fig. 3. Total C content in the soil profile to 21 cm over 12 yr in the long-term plowed and no-tillage plots at Horseshoe Bend. Points represent means with standard error bars.

Data from P-1 watershed showed an increase over initial C content of approximately 11 Mg C ha^{-1} after 20 yr of NT management (Bruce and Langdale, 1997), giving a rate of increase of ca. 0.6 Mg C ha^{-1} yr^{-1} (data not shown). Soils in the watershed were depleted of C at the beginning of the study (17 Mg C ha^{-1}) but increased to 28 Mg C ha^{-1} (Table 1). Continuing at this rate of increase, P-1 watershed would be expected to reach the predicted regional equilibrium (39 Mg C ha^{-1}) in about 16 more years, or a total of ca. 36 yr since initiation of NT management. This time period is consistent with the chronosequence estimates in Fig. 1, although managed systems might be expected to reach a higher equilibrium value. It is noteworthy that moderately eroded soils with higher clay content may sequester more C than the slightly eroded soils with a sandier textured Ap horizon (Langdale et al., 1987; Bruce and Langdale, 1997).

Short-term impacts of CT and NT management on soil C content in the small plots newly taken out of sod at Griffin and Horseshoe Bend are shown in Table 2. No significant changes occurred during a 3 yr period, although C concentrations declined in the 0–5 cm depth and increased in the 5–15 cm depth in CT (Hendrix, 1997; data not shown). The trend was the same at both sites even though soil C content was nearly 2-fold higher at Griffin than at Horseshoe Bend. Similar redistributions of C in the soil profile but no

Table 2
Soil C content (Mg C ha^{-1} to 25 cm) initially and after 3 yr of sod, no-tillage (NT) or conventional tillage (CT) management in the short-term plots. Values are means (n=4) with standard errors in parentheses

		After 3 years		
Site	Initial	Sod	NT	CT
Horseshoe Bend	21.24[a]	19.64	21.68	23.10
	(1.39)	(1.12)	(1.12)	(1.21)
Griffin	38.11[a]	42.88	43.32	44.72
	(4.32)	(4.01)	(5.94)	(6.26)
Dawson Field	16.75[b]	—	16.25	—
	(0.90)		(0.73)	
Dawson Field	22.51[c]	—	25.19	—
	(1.51)		(2.46)	

[a] Long-term sod.
[b] Long-term cultivated (slightly eroded Cecil).
[c] Long-term cultivated (severely eroded Pacolet).

net loss of total C have been observed previously by Tiessen and Stewart (1983) in a prairie soil. The small plot data are consistent with the relatively slow decrease or no change in soil C content observed in the long-term plots at these sites (Figs. 2 and 3).

Data from the short-term plots installed in the recently converted NT treatments on Dawson Field at Watkinsville are also shown in Table 2. After 3 yr of NT management, no significant changes in C content were observed in the slightly eroded, sandy Cecil soil. The severely eroded Pacolet soil showed a small but not significant increase in C of ca. 1 Mg C ha^{-1} yr^{-1}, slightly higher than the 0.6 Mg C ha^{-1} yr^{-1} increase observed over 20 yr in the nearby P-1 watershed. These results support the previous suggestion that elevated clay content may enhance C sequestration in eroded surfaces.

4. Conclusions

Observed values for soil C content ranged from 14 to 48 Mg C ha^{-1} across a variety of soil types, topographic positions and management histories on the Georgia Piedmont. The low values may represent a minimal amount of physically and chemically protected C (Tisdall and Oades, 1982) remaining in these soils after long periods of intensive cultivation and erosion. Functionally, this C probably constitutes a slow or passive pool of C (Parton et al., 1987) with little contribution to soil biological activity or fertility. The highest value is from a long-term NT soil which has been managed for high productivity and organic matter input (Hargrove et al., 1982). Characteristics of the organic matter pools in this soil were not measured in this study, but other long-term NT soils in the region show increased microbial and mineralizable C and N compared to CT soils (Beare et al., 1994), indicating enhanced native fertility associated with organic matter accumulation. Knowledge of the size and nature of organic pools in native and managed soils at equilibrium is needed to estimate the ultimate fertility and C sequestering capacity of southern Piedmont soils.

It is not possible to estimate a single regional equilibrium level for soil C because it will be highly dependent on soil texture, management systems, etc. The value of 39 Mg C ha^{-1} (Table 1) calculated from Post et al. (1985) may be a reasonable average for native ecosystems in the region, and is supported by some of our data as well as by preliminary simulation modeling (Hendrix et al., 1996). However, the variance around such an average needs to be characterized; for example, a value of 51 Mg C ha^{-1} has been measured in a bottomland Piedmont forest soil (E.T. Elliott, personal communication), and values less than 39 Mg C ha^{-1} might be expected from short rotation pine forests, which are extensive across the southern Piedmont. Simulation modeling of soil C dynamics under various edaphic and management scenarios are needed to supplement observational data and allow for a more complete assessment of the potential for soils in this region to accumulate C.

Acknowledgements

This work was supported by grant no. BSR-8818302 from the National Science Foundation to the University of Georgia Research Foundation, Inc. We are grateful to M.H. Beare, R.R. Bruce, Weixin Cheng, D.C. Coleman, D.A. Crossley, Jr., K.M Hill, K. Howard, Shuijin Hu, G.W. Langdale, B. Lankester, B. Weise, and P. van Vliet for their contributions to this project.

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