RESEARCH

Impact of the return to cultivation on carbon (C) sequestration

H.A. Torbert, S.A. Prior, and G.B. Runion

ABSTRACT: A growing body of science indicates that carbon (C) can be sequestered in soil as a result of changes in land management. Generally, this requires land be taken out of cultivated agriculture; however, it has been postulated that gains in soil C can be quickly eliminated with return to cultivation. The objective of this study was to examine the impact of converting land back into cultivated agricultural management on C sequestration within two different soil types. Soil samples from nine depth increments (0-5, 5-10, 10-15, 15-30, 30-45, 45-60, 60-75, 75-90, 90-105 cm) (0-2, 2-4, 4-6, 6-12, 12-18, 18-24, 24-30, 30-36, 36-42 in) were collected from a Blanton loamy sand (loamy, siliceous, semiactive, thermic Grossarenic Paleudults) and an Urbo clay loam (fine, mixed, active, acid, thermic Vertic Epiaquepts) in central Alabama, USA, that were under different land management systems. Management systems included forest, permanent pasture, and pasture converted to continuous cultivation for 1 and 2 years. Within the loamy sand soil, land management also included continuously cultivated (>40 yr), weedy-fallow for 5 years, and returned to cultivation after weedy-fallowed for 4 years. Soil samples were analyzed for total nitrogen (N), organic C, and soil C:N ratio. The clay loam soil had higher capacity to sequester C [147 Mg ha^{-1} (66 tons ac^{-1}) for pasture], than the loamy sand soil [74 Mg ha^{-1} (33 tons ac^{-1}) for pasture]. Little difference was observed between the forested soil and the permanent pasture in the clay loam soil, with 139 Mg ha^{-1} (62 tons ac^{-1}) and 147 Mg ha^{-1} (66 tons ac^{-1}), respectively. In the loamy sand soil, large differences were observed for C between the forested and the permanent pasture sites, with 127 Mg ha^{-1} (57 tons ac^{-1}) and 74 Mg ha^{-1} (33 tons ac^{-1}), respectively. Results indicate that the vulnerability of soil to lose sequestered C will likely depend on soil type. The clay loam soils, although having higher levels of C, lost 55% of its C with 2 years of cultivation, while the loamy sand soil showed little significant loss of C content [below 0-5 cm (0-2 in)] within the same time frame.

Keywords: C sequestration, land management, organic C, soil type, tillage, total N

Agro-ecosystems are important in the global context because of the large carbon dioxide (CO_2) flux to the atmosphere, and also because carbon (C) storage in agro-ecosystems can be sensitive to management practices such as tillage and cropping systems (West and Post, 2002). The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) (Kyoto Protocol, 1998) commits developed nations to reduce greenhouse gas emissions to 5% below the 1990 level. However, in addition to reduction in industrial emissions, the protocol may allow for developed nations to meet their reduction limits by C sequestration in terrestrial sinks. While the U.S. has indicated that it will not participate in the agreement, the U.S. government has undertaken efforts to target C sequestration in U.S. forests and croplands (USDA Fact Sheet, 2003).

Recent estimates of terrestrial C sinks have been developed. The Intergovernmental Panel on Climate Change estimated that the C sequestration potential of grazing lands and timberlands is 0.53 t C ha^{-1} yr^{-1} (0.24 tons C ac^{-1} yr^{-1}), while that of crop lands is 0.32 t C ha^{-1} yr^{-1} (0.14 tons C ac^{-1} yr^{-1}) (Kimble et al., 2002). Lal et al. (1998) estimates that croplands have the potential to sequester 142 Mt C yr^{-1} m^{-1}depth (156 million tons C yr^{-1} 3.3 ft^{-1} depth). Mitchell et al. (1996) examined the impact of the Conservation Reserve Program (CRP) and conservation tillage using the Environmental Policy Integrated Climate (EPIC) model and the National Resources Inventory (NRI) database and found that agricultural soils would be a sink for C in the central United States. Also, using the EPIC model, Dick (1996) estimated that widespread conversion to no-till production in the Corn Belt of the United States could sequester 3.3 Mt C yr^{-1} (3.6 million tons C yr^{-1}) for the next 100 years. Converting crop production land to perennial grass cover associated with CRP in Texas, Kansas, and Nebraska would result in an estimated increase in total organic C of 1.1 t of C ha^{-1} yr^{-1} (0.49 tons C yr^{-1}) (Gebhart et al., 1994). In a more recent review, West and Post (2002) estimated that conversion of conventional tillage to a no-tillage system could potentially sequester 0.57 t C ha^{-1} yr^{-1} (0.25 tons C yr^{-1}). Follett (2001) reported that conversion to improved tillage and cropping systems in the United States could potentially sequester 30-105 Mt of C yr^{-1} (33-116 million tons of C yr^{-1}).

The Kyoto protocol also included the concept of emissions trading, whereby the national limits of greenhouse gas reductions could be traded (Marland et al., 2001b). This included C emission reduction by sequestration of C in terrestrial ecosystems (although sequestration in cropland has not been resolved). This concept has led to efforts to develop economic incentives for land management systems that would sequester C for a greenhouse gas emission trading market. For example, the 2002 U.S. Department of Agriculture (USDA) farm bill legislates provisions to pay farmers using agricultural practices that boost soil C content (McInnis, 2003). These efforts could lead to producers being paid for environmental credits through the free market (Abbott, 2002). However, there are several concerns regarding the potential of using terrestrial C sinks to offset greenhouse gas emission. These concerns include knowing the duration of the increased C sequestration and verification

H. Allen Torbert is a soil scientist with the U.S. Department of Agriculture-Agricultural Research Service, National Soil Dynamics Laboratory, Auburn, Alabama. **Stephen A. Prior** is a plant physiologist with the U.S. Department of Agriculture-Agricultural Research Service, National Soil Dynamics Laboratory, Auburn, Alabama. **G. Brett Runion** is a soil microbiologist with the U.S. Department of Agriculture-Agricultural Research Service, National Soil Dynamics Laboratory, Auburn, Alabama.

Table 1. Soil texture, pH, and extractable nutrients of study soils.[†]

Soil	Texture	pH	P	K	Mg	Ca	Mn	Na	B
		$\mu g\ g^{-1}$							
Urbo	clay loam	5.2	6.7	68.8	86.7	1891.0	55.8	23.6	0.4
Blanton	loamy sand	5.4	28.9	33.4	63.0	219.2	17.8	5.7	0.2

[†]**Values represent means composited soil samples taken from the top 20 cm at each sample site of each soil type.**

that sequestration took place because of a land management change (Marland et al., 2001a; Marland et al., 2001b). Also, when C is sequestered, how long will it stay there (Marland et al., 2001a;b)? The objective of this study was to examine the potential impact of management decisions such as returning land to conventional tillage systems on C sequestration.

Methods and Materials

A study area was selected in central Alabama, which contained (within a 1 km radius) several land management systems on a Blanton loamy sand soil (loamy, siliceous, semiactive, thermic Grossarenic Paleudults) and an Urbo clay loam soil (fine, mixed, active, acid, thermic Vertic Epiaquepts) (Table 1). In this study area, sites were identified to represent soil conditions that resulted from soil tillage management decisions. Specifically, within each of these two soil types, an undisturbed forest and a permanent pasture (maintained for at least 40 years) site were selected. Within the permanent pasture on the clay loam soil, sites were located that had been converted to cultivated agriculture for 1 and 2 years. Within the permanent pasture on the loamy sand soil, sites were located that had been converted to cultivated agriculture for 2 years. The sites were initially plowed to a depth of 30 cm (12 in) with a mold board plow to break up the sod. They were subsequently plowed with a breaking harrow to approximately 15 cm (6 in) and with a smoothing harrow to approximately 10 cm (4 in) before planting. Each of the areas in the pasture that were cultivated were planted to wheat (*Triticum aestivum* L.) and received 336 kg ha^{-1} (300 lb ac^{-1}) of 13-13-13 fertilizer. In addition, within the loamy sand soil, an area continuously cultivated for cotton (*Gossypium hirsutum* L.) production for at least 40 years was located. Within this cultivated area, sites were selected that reflected the effects of three management decisions: 5 years of a conservation tillage system, 5 years of weedy-fallow, and return to conventional tillage after 4 years of weedy-fallow. The conservation tillage system was a strip-tillage consisting of planting rye (*Secale cereale* L.) as a winter cover after cotton harvest, and planting cotton into a herbicide-terminated rye cover. Application of N fertilizer was made at a rate to supply 101 kg N ha^{-1} (90 lb N ac^{-1}) as urea/ammonia nitrate (32-0-0) each year. Other cultural practices for production of cotton and wheat (including P and K fertilizer) followed guidelines recommended by the Auburn University Soil Testing Laboratory. The weedy-fallow site consisted of no soil tillage or weed control; the site was dominated by grassy weed species and was occasionally mowed to prevent invasion of woody plant species. The third management site was located in the weedy-fallow area, but had been plowed and planted in a conventional tillage manner. This site was planted to pearl millet (*Pennisetum americanum* [L.] Leeke) and fertilized with 336 kg ha^{-1} (300 lb ac^{-1}) of 13-13-13 fertilizer.

General soil characteristics for the two soil types given on Table 1 were determined from composite of six soil samples [2 cm (0.79 in) diameter] taken from a 0-20 cm (0-8 in) depth increment at each study site and averaged across soil types. Soil samples were also analyzed for pH and extractable concentrations P, K, Mg, Ca, Mn, Na, and B by the Soil Testing Laboratory, Auburn University using procedures outlined by Hue and Evans (1986). Briefly, the soils were extracted using Mehlich 1 extractant (Mehlich, 1953) and measured by inductive coupled plasma spectrophotometry (ICP 9000, Thermo Jarell-Ash Corporation, Franklin, Massachusetts).

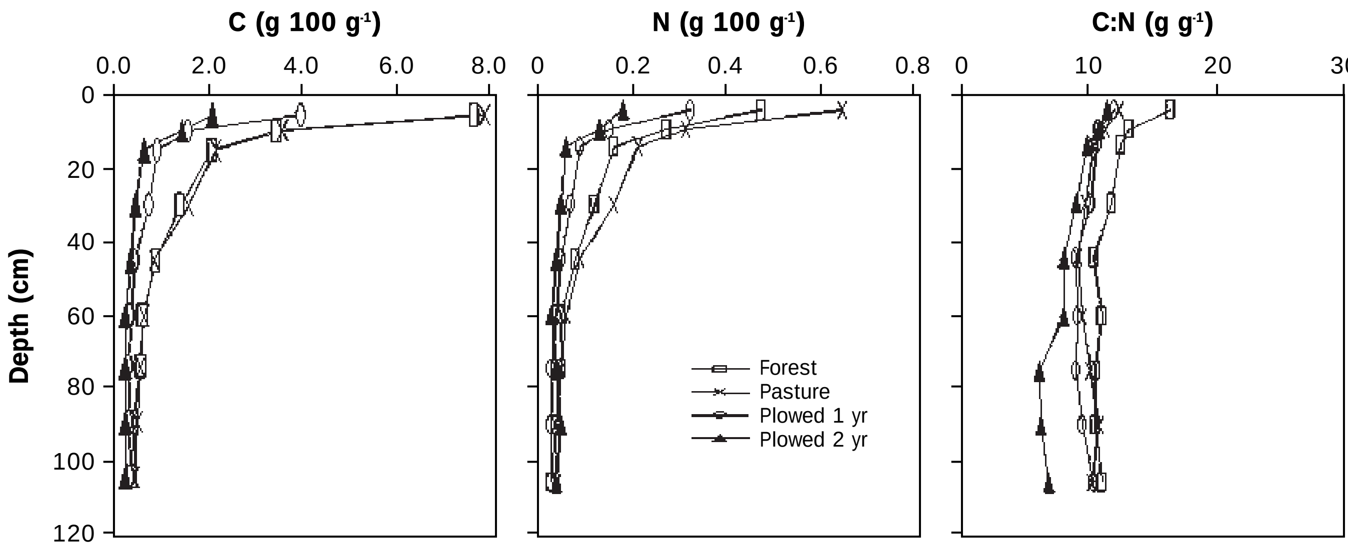
Soil samples were collected from each site at 0-5, 5-10, 10-15, 15-30, 30-45, 45-60, 60-75, 75-90, and 90-105 cm (0-2, 2-4, 4-6, 6-12, 12-18, 18-24, 24-30, 30-36, 36-42 in) depth increments to investigate management system effects on soil C and N. Three soil cores [3.8 cm (1.5 in) diameter] were collected from each of four replicate blocks in each management system. Cores were extracted using a custom-made telescoping soil coring device assisted by a modified commercial hydraulic post driver mounted to the front of a small tractor. The tractor hydraulic system powered both the telescoping device and the post driver. Soil samples were stored at 5˚ C (41˚ F) until processing. Subsamples of the soils were dried [55˚ C (131˚ F)], ground to pass a 0.15 mm (0.006 in) sieve, and analyzed for total N and C concentration on a LECO CN 2000 (LECO Corporation, Saint Joseph, Michigan). Bulk density was determined on core segments to determine total C and N content. Soil C:N ratio was calculated as the soil organic C content divided by the soil total N content. Microbial activity was determined by a modified dehydrogenase assay described by Tabatabai (1982) that measures total microbial numbers or microbial activity by formation of formazan concentrations.

No long-term conventional tillage systems were available at the study area, however, a different study area [within 10 km (6 mile)] having long-term conservation and conventional tillage histories was available. The soil at this study area was a Marvyn sandy loam (fine-loamy, Kaolinitic, thermic Typic Kanhapludults), which is a closely associated soil series to Blanton. The conservation tillage system used on the Marvyn soil series was similar to that used on the Blanton soil series and details were reported by Torbert et al. (2002). Briefly, the conservation tillage system was a strip-tillage consisting of planting rye (*Secale cereale* L.) as a winter cover after cotton harvest, and planting cotton into a herbicide-terminated rye cover with an in-row subsoiler planter. In the Marvyn soil series study, soil samples were collected from three different fields managed with the conservation tillage for more than 25 years, and from three adjacent fields managed with conventional tillage practices. Ten soil cores [2 cm (0.8 in) diameter] were collected from each field site and composited by soil depths of 0-5, 5-10, and 10-20 cm (0-2, 2-4, and 4-8 in). Soil samples were analyzed for total N and C concentration as described above.

The experimental design was a completely randomized block design of 10 management system treatments with four replications. The triplicate samples (cores) were averaged prior to statistical analysis. Statistical analyses were performed using the Proc Mixed procedure of SAS (Littell et al., 1996), and means were separated at an *a priori* 0.05 probability level.

Figure 1

Soil organic carbon (C) concentration, total nitrogen (N) concentration, and C:N ratio in a Urbo clay loam soil in forest, pasture, or plowed pasture for one or two years.



Results and Discussion

As expected, soil organic C concentration (Figures 1-3) and organic C content (Tables 2 and 3) were stratified in the soil profile, with much higher organic C levels noted in the top of the profile compared to the deeper soil depths. Likewise, the total N concentration (Figures 1-3) and total N content (Table 4 and 5) were stratified, with the highest levels observed at the soil surface. The area of greatest stratification was in the top three soil depths [0-5, 5-10 and 10-15 cm (0-2, 2-4, and 4-6 in)], with dramatic changes observed in both soil organic C and total N concentration and content. The depth increment studied was increased below 30 cm (12 in) so that the C content was greatly increased due to larger area included in the sampling below this depth. Below 30 cm (12 in), few differences were observed within soil depths among different management sites. The concentration of organic C and total N in the 0-5 cm (0-2 in) depth was very high in both the pasture and the forested sites. This may have been due to the presence of a duff layer in these soils, even though efforts were made to remove the duff at the time of sampling and when soil samples were sieved prior to further processing and analysis.

Large differences were observed for soil C

Figure 2

Soil organic carbon (C) concentration, total nitrogen (N) concentration, and C:N ratio in a Blanton loamy sand soil in forest, pasture, or plowed pasture for one year.

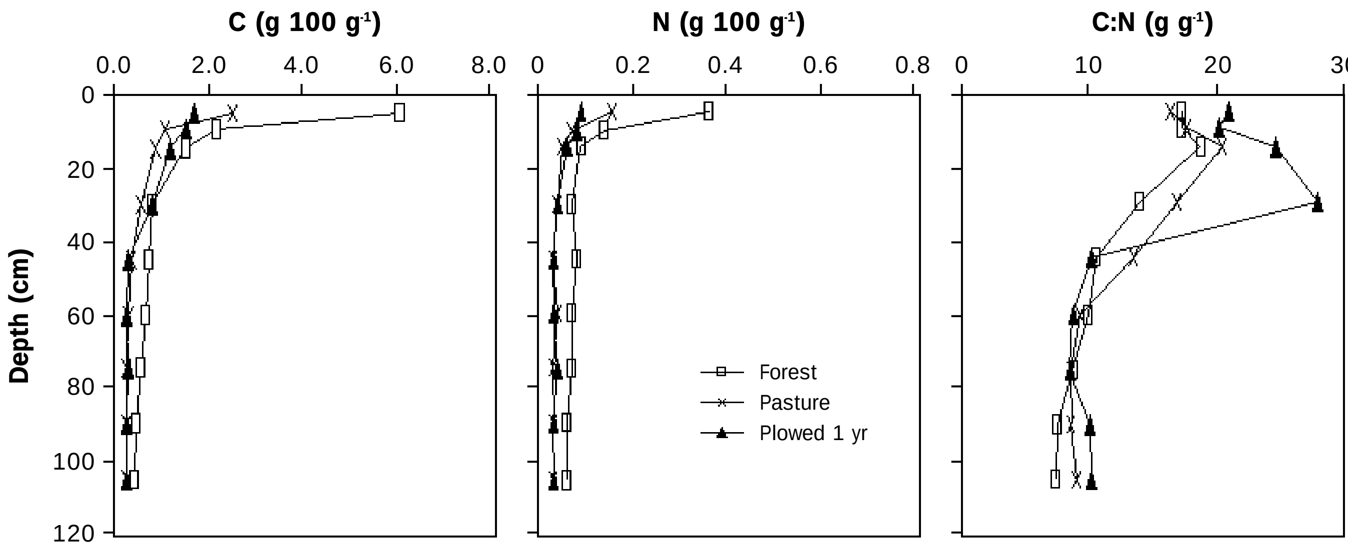
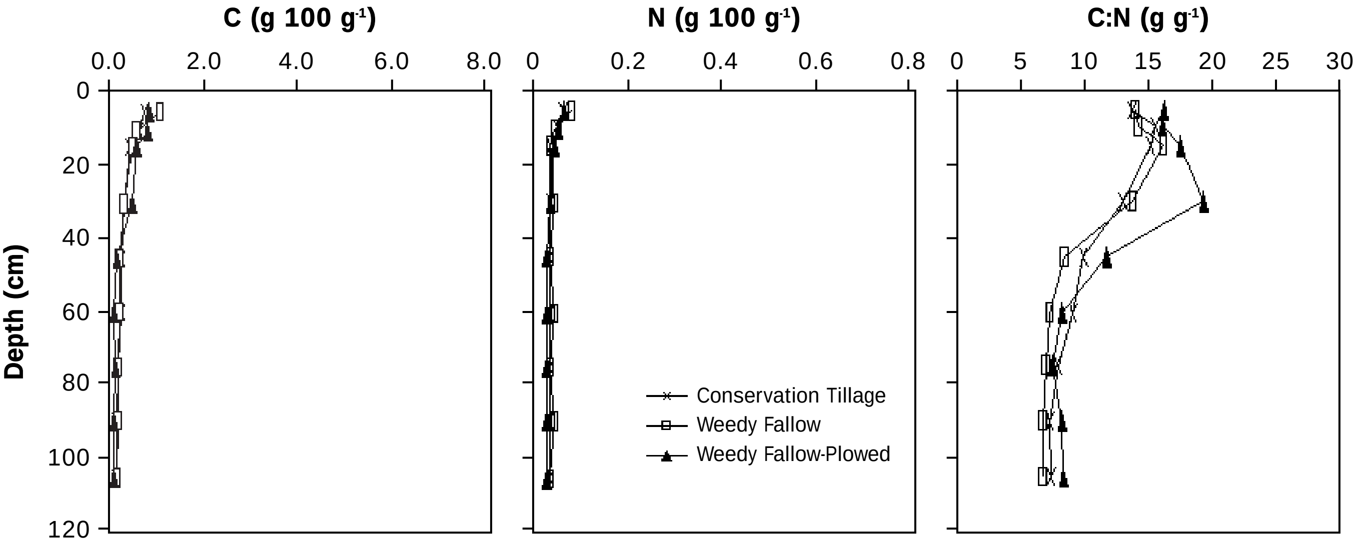


Figure 3
Soil organic carbon (C) concentration, total nitrogen (N) concentration, and C:N ratio in a Blanton loamy sand soil in cultivation: Conservation tillage, weedy-fallow, and weedy-fallow plowed.



concentration (*P<0.0001*) for comparable management systems between the loamy sand soil and the clay loam soil (Figures 1 and 2). For example, at the 0-5 cm (0-2 in) depth, the forested clay loam soil had a total C concentration of 7.7 g 100 g^{-1} (7.7 %) compared to 6.1 g 100 g^{-1} (6.1 %) for the forested loamy sand soil. Likewise, in the permanent pasture soil [0-5 cm (0-2 in)] total C concentration was 7.9 g 100 g^{-1} (7.9 %) for the clay loam, compared to 2.5 g 100 g^{-1} (2.5 %) for the loamy sand soil. These differences were generally observed for all of the comparable management systems sampled in this study. This indicated the clay loam soil had a higher potential to sequester C than the loamy sand soil.

In the clay loam soil, few differences were observed between the forested soil and the permanent pasture for organic C levels (Figure 1; Table 2). However, when the pasture was plowed for 1 or 2 yrs, large reductions in organic C were noted throughout the soil profile; further, additional significant reductions were also seen for organic C content for 2 yrs compared to the 1 yr of cultivation in the 0-5 (0-2 in) and 10-15 cm (4-6 in) depths (Table 2).

Table 2. Total organic carbon (C) content in a Urbo clay loam soil in forest, pasture, or plowed pasture at 0-5, 5-10, 10-15, 15-30, 30-45, 45-60, 60-75, 75-90, and 90-105 cm depths.†

Depth (cm)	Forest	Pasture permanent	Pasture plowed 1 yr	Pasture plowed 2 yr
	C (Mg ha^{-1})			
0-5	26.23 a	28.17 a	18.17 b	12.08 c
5-10	17.56 a	17.22 a	10.32 b	9.26 b
10-15	11.70 a	11.87 a	6.65 b	5.50 c
15-30	25.82 a	28.79 a	15.43 b	10.99 b
30-45	17.98 a	17.32 a	9.79 b	7.97 b
45-60	12.39 ab	13.05 a	7.96 bc	5.90 c
60-75	10.52 a	11.32 a	6.34 b	5.33 b
75-90	8.81 a	10.10 a	6.07 b	5.79 b
90-105	7.59 ab	8.96 a	7.67 ab	5.44 b

† **Values represent means of 4 replications. Means within a row followed by the same letter do not differ significantly (0.05 level). Note change in soil depth increment beginning at depth 15 cm.**

For the most part, the total N levels (concentration and content) in the clay loam soil followed the patterns observed for organic C in the upper soil depths (Figure 1; Table 4). The exception was that total N levels were generally higher in the permanent pasture compared to the forest soil. As was noted for organic C, a significant reduction in the total N content was observed when the permanent pasture was plowed. Below the 45 cm (18 in) depth, no significant difference for total N content was noted for any of the management systems (Table 4). The higher levels of N in the pasture may have reflected past fertilizer N additions; however, it is clear that the permanent pasture has the capacity to hold N since no N fertilizer was added during the 10 years prior to sampling. On the other hand, it is clear that once plowing begins, soil N can disappear quickly, as was observed with the 1 and 2 yrs of plowing. This occurred even though additional fertilizer was added to these areas once crop production began.

The C:N ratio of the clay loam soil was very stable throughout the soil profile (Figure 1), despite drastic changes in the organic C and total N levels. The C:N ratio was generally significantly higher in the forest soils compared to the pasture soils down to 60 cm (24 in). This was likely due to the stable state represented by the forested soils over many years, where the soil N inputs are influenced by trunk and root production. Below 60 cm (24 in), the pasture that was plowed for 2 yrs

Table 3. Total organic carbon (C) content in a Blanton loamy sand soil in forest, pasture, or plowed pasture at 0-5, 5-10, 10-15, 15-30, 30-45, 45-60, 60-75, 75-90, and 90-105 cm depths.†

Depth (cm)	Forest	Pasture permanent	Pasture plowed 2 yr	Conservation tillage	Weedy-fallow	Weedy-fallow plowed
	C (Mg ha-1)					
0-5	26.46 a	15.96 b	11.06 c	7.11 d	8.84 cd	7.16 d
5-10	14.67 a	8.75 bc	10.73 b	6.33 cd	5.28 d	6.64 cd
10-15	10.42 a	7.09 b	9.25 a	4.64 c	4.91 c	4.83 c
15-30	17.35 ab	12.81 cd	19.69 a	9.81 d	9.87 d	13.82 bc
30-45	14.87 a	7.35 b	5.55 c	8.2 b	7.13 bc	5.47 c
45-60	13.36 a	5.64 bc	4.26 cd	7.31 b	7.06 b	3.81 d
60-75	11.21 a	4.80 bc	5.79 bc	6.39 b	5.85 bc	3.96 c
75-90	9.21 a	4.26 cd	4.92 bc	5.61 b	5.89 b	3.62 d
90-105	8.94 a	4.91 bc	4.63 bc	5.28 bc	5.91 b	4.03 c

† Values represent means of 4 replications. Means within a row followed by the same letter do not differ significantly (0.05 level). Note change in soil depth increment beginning at depth 15 cm.

had a C:N ratio that was significantly lower compared to the other sites (Figure 1). This may have been due to the downward movement of N through the soil profile as N was released from the upper soil depths during oxidation of organic matter following plowing.

In the loamy sand soil, large differences were observed for organic C concentration (Figure 2) and organic C content (Table 3) between the forested and the permanent pasture sites throughout the soil profile, especially the 0-5 cm (0-2 in) depth. However, unlike the clay loam soil, little reduction was observed for soil organic C below the 0-5 cm (0-2 in) depth under the pasture after 2 yrs of plowing compared to the permanent pasture, (Figure 2; Table 3). In fact, an increase in organic C content was observed at the 10-15 (4-6 in) and 15-30 cm (6-12 in) depth (Table 3). This would be consistent with the tillage moving the residue to these deeper depths with the mold board plowing. Similar results have been noted by Allmaras et al. (1996) with moldboard plowing of oat residue.

Total N concentration (Figure 2) and total N content (Table 5) in the loamy sand soil was also stratified in the soil profile, with soil total N closely following the patterns observed for organic C in the soil profile at all management sites. Interestingly, unlike the clay loam soil, total N was highest throughout the soil profile for the forest compared to the pasture. This was despite the fertilizer applications that were made to both the pasture and the plowed pasture in the loamy sand sites. In the pasture sites, hay production resulted in substantial nutrient removal. Nevertheless, the data indicates that fertilizer application was not a major contributor to C sequestration or soil N retention in this soil type.

In the cultivated sites, soil C was much lower than in sites maintained in long-term pasture or forest (Table 3; Figure 3). Stratification of soil C was observed with soil depth, although much less than was seen in the forest or pasture sites. Few significant differences were observed for organic C between the conservation tillage, weedy-fallow, or plowed weedy-fallow sites in the top 0-15 cm (0-6 in) (Figure 3; Table 3). As was observed with the plowing of the permanent pasture, a significant increase in organic C was observed at the 15-30 cm (6-12 in) depth, which may be a result of physical movement of residue from the soil surface (Allmaras, 1996). Below 45 cm (18 in), some reduction in organic C was observed for plowed weedy-fallow, but the results were not consistent.

The lack of significant reduction in organic C in the top 0-15 cm (0-6 in) depth when the weedy-fallow was plowed compared to the conservation tillage or the weedy fallow is in contrast to other studies which have indicated that conversion to conservation tillage leads to increases in organic C concentration near the soil surface (Torbert et al., 1997; Potter et al., 1997; Reeves, 1997). The ability of the soil to sequester C may be dependent not only on residue management, but also on crop sequence (Potter et al., 1997), and climate (Reeves, 1997; Potter et al., 1998). Furthermore, the time required for significant C sequestration may be greatly impacted by soil type.

In this study, no increases were seen for the weedy-fallow site and no reductions were observed for the plowed weedy-fallow site

Table 4. Total nitrogen (N) content in a Urbo clay loam soil in forest, pasture, or plowed pasture at 0-5, 5-10, 10- 15, 15-30, 30-45, 45-60, 60-75, 75-90, and 90-105 cm depths.†

Depth (cm)	Forest	Pasture permanent	Pasture plowed 1 yr	Pasture plowed 2 yr
	N (Mg ha-1)			
0-5	1.61 b	2.31 a	1.51 b	1.05 c
5-10	1.33 a	1.54 a	0.96 b	0.86 b
10-15	0.93 b	1.14 a	0.62 c	0.45 d
15-30	2.19 b	2.99 a	1.52 c	1.22 c
30-45	1.68 a	1.89 a	1.08 b	0.99 b
45-60	1.12 ab	1.37 a	0.87 b	0.73 b
60-75	0.98 a	1.12 a	0.71 a	1.17 a
75-90	0.81 a	0.94 a	0.65 a	1.22 a
90-105	0.67 a	0.88 a	0.73 a	1.10 a

† Values represent means of 4 replications. Means within a row followed by the same letter do not differ significantly (0.05 level). Note change in soil depth increment beginning at depth 15 cm.

Table 5. Total nitrogen (N) content in a Blanton loamy sand soil in forest, pasture, or plowed pasture at 0-5, 5-10, 10-15, 15-30, 30-45, 45-60, 60-75, 75-90, and 90-105 cm depths.†

Depth (cm)	Forest	Pasture permanent	Pasture plowed 2 yr	Conservation tillage	Weedy-fallow	Weedy-fallow plowed
	N (Mg ha^{-1})					
0-5	1.57 a	0.99 b	0.54 cd	0.52 cd	0.64 c	0.44 d
5-10	0.86 a	0.50 bc	0.54 b	0.40 bc	0.37 c	0.41 bc
10-15	0.56 a	0.35 bc	0.38 b	0.31 bc	0.31 bc	0.27 c
15-30	1.28 a	0.77 bc	0.70 c	0.77 bc	0.79 bc	0.70 c
30-45	1.46 a	0.57 c	0.57 c	0.86 b	0.90 b	0.49 c
45-60	1.41 a	0.63 d	0.54 d	0.84 c	1.07 b	0.51 d
60-75	1.36 a	0.59 c	0.76 bc	0.85 b	0.93 b	0.59 c
75-90	1.32 a	0.53 c	0.52 c	0.85 b	0.98 b	0.47 c
90-105	1.31 a	0.56 cd	0.49 d	0.80 bc	0.96 b	0.53 d

† **Values represent means of 4 replications. Means within a row followed by the same letter do not differ significantly (0.05 level). Note change in soil depth increment beginning at depth 15 cm.**

for soil organic C and total N in the top 0-15 cm (0-6 in), however, no comparison to conventional tillage management was available at this location. A plausible explanation is that C sequestration in loamy sand is very slow and detectable differences in weedy-fallow and conservation tillage systems will take more than five years to be distinguishable. At the same time, plowing for one year did not impact measurable organic C loss, as was observed with the clay loam soil. This is in general agreement with results observed from plowing the pasture in this same loamy sand soil.

While no comparison between long term conservation tillage and conventional tillage was available at the loamy sand site, soil samples collected from a different study area [within 10 km (6 mi)] having long-term conservation and conventional tillage histories were available. The soil at this site was a Marvyn sandy loam, which is a closely associated soil series to Blanton. In this area, soil samples were collected from fields managed with conservation tillage for more than 25 yr, and from fields managed with conventional tillage practices. The organic C and total N concentrations noted for this study area were dramatically higher for the conservation tillage compared to conventional tillage (Table 6). Interestingly, the soil organic C and N concentration for the conventional tillage at the Marvyn sandy loam soil site was lower than observed for the soil samples in Blanton loamy sand site (conservation tillage, weedy-fallow and plowed weedy-fallow), but not nearly as high as those observed after 25 yrs of conservation tillage (Table 3 and 6). This is further evidence that conservation tillage and weedy-fallow management had resulted in sequestered C in the five years these managements were imposed. However, it also gave evidence that plowing weedy-fallow sites may not have an immediate impact on C losses as was observed with the clay loam soil.

The C:N ratio for the loamy sand soil was distinctively different than that observed for the clay loam soil (Figures 1-3). While the C:N ratio was relatively stable in the clay loam, both across soil depths and study sites, the C:N ratio of the loamy sand soil differed both between sites and soil depths. With the loamy sand soil, the C:N ratio increased greatly with soil depth down to about 30 cm (12 in) and then was reduced to a steady level at deeper depths (Figures 2 and 3). While this effect was observed at all sites, it was more pronounced at sites with increased plowing; i.e., the pasture plowed for 2 years (Figure 2) and the weedy-fallow that was plowed (Figure 3). The increased C:N ratio is caused by a higher level of organic C content relative to the total N content, especially at the 10 to 15 (4-6 in) and 15 to 30 cm (6-12 in) depths. This effect was not predicted from the organic C and total N concentrations observed on the same graphs (Figures 2 and 3). However, the C:N ratio was calculated from the organic C and total N contents, which include changes in soil bulk density (data not shown). This 10 to 30 cm (4-12 in) depth is more susceptible to the formation of traffic pans from tillage operations. While few significant differences were observed between the organic C and total N content levels at depths where the greatest inflection occurred (10-30 cm), the C:N ratio was significantly different. This demonstrates that the C:N ratio is sensitive to small changes in the soil organic C and total N content. However, since this effect was primarily the result of the soil physical change (i.e., increased bulk density), it also indicates that care must be taken in interpretation of the biological impacts of soil C:N ratio. Also, this change demonstrates the importance of not only measuring C and N concentrations, but also considering changes in C and N content.

Total soil C and N content, summed over 0 to 15, 15 to 105, and 0 to 105 cm (0-6,

Table 6. Concentration of total nitrogen (N) and organic carbon (C) in a Marvyn sandy loam soil with conventional tillage and conservation tillage (strip-tillage) cropping system at 0-5, 5-10, and 10-20 cm depth.†

Depth (cm)	Conventional tillage	Conservation tillage	Conventional tillage	Conservation tillage
	N (g 100 g^{-1})		C (g 100 g^{-1})	
0-5	0.04 a	0.10 b	0.64 a	1.28 b
5-10	0.04 a	0.06 b	0.64 a	0.84 b
10-20	0.04 a	0.04 a	0.63 a	0.64 a

† **Values represent means of 3 replications. Means within a row for an elemental concentration followed by the same letter do not differ significantly (0.05 level). Samples collected from farmers field on similar loamy sand (similar soil type) within 8 km of the study area.**

Table 7. Effect of land management system on organic carbon (C) and total nitrogen (N) content in the 0-15, 15-105 and 0-105 cm depth increments.†

Soil type History	Organic C 0-15 cm	Organic C 15-105 cm	Sum Organic C 0-105 cm	Total N 0-15 cm	Total N 15-105 cm	Sum Total N 0-105 cm
	(Mg ha^{-1})					
Urbo Clay Loam						
Forested	55.5 a	83.1 a	138.6 a	3.87 a	7.45 ab	11.32 a
Pasture - Permanent	57.3 a	89.5 a	146.8 a	5.00 b	9.19 a	14.19 ab
Plowed 1 yr	35.1 b	53.3 b	88.4 b	3.09 c	5.55 b	8.64 b
Plowed 2 yr	25.8 c	41.1 b	67.3 c	2.36 d	6.44 ab	8.80 b
Blanton Loamy Sand						
Forested	51.6 a	74.9 a	126.5 a	3.00 a	8.14 a	11.13 a
Pasture - Permanent	31.8 b	39.8 bc	71.6 bc	1.85 b	3.64 d	5.49 cd
Plowed 2 yr	31.0 b	44.8 b	75.9 b	1.47 c	3.58 d	5.05 de
Conservation-tillage	18.1 c	42.6 bc	60.7 cd	1.24 c	4.98 c	6.22 c
Weedy-fallow	19.0 c	41.7 bc	60.8 cd	1.32 c	5.99 b	7.31 b
Weedy-fallow - plowed	18.6 c	34.7 c	53.3 d	1.12 c	3.28 d	4.40 e

† Values represent means of 4 replicates. Means within a column (within a soil type) followed by the same letter do not differ significantly (0.05 level).

6-42, and 0-42 in) depths are presented in Table 7. With the forest and pasture sites, approximately 60% of the soil C measured in 0 to 105 cm (0-42 in) was contained in the top 15 cm (6 in), while in the cultivated sites, due to the smaller overall C content, approximately 70% of the total soil C was contained in the top 15 cm (6 in). In the clay loam soil, no differences were observed between the permanent pasture and the forest sites for soil C content, but reductions occurred between the pasture and the forest sites in the loamy sand soil (Table 7). In the top 30 cm (12 in) of the clay loam soil, a 38% reduction in soil C was observed after the first year of cultivation, and a 55% reduction in soil C was observed after 2 years of cultivation (Table 7). Similar reductions were observed when summed for the 0 to 105 cm (0-42 in) depth (Table 7). Unlike the clay loam soil, the loamy sand soil showed no significant reduction in soil C content after plowing (Table 7). Likewise, while soil C content was much less than in the pasture sites in the loamy sand soil, the cultivated sites were not significantly different from each other (Table 7).

Soil microbial activity was measured through a dehydrogenase assay to examine differences in either soil microorganism populations or microbial activity (Table 8). While large differences were seen between soil organic C and total N between sites and soil depths (Tables 2-7), only small difference was observed for microbial activity. For the clay loam soil, the only significant difference was for the pasture that had been plowed for 2 years compared to the other clay loam sites (Table 8). This difference was observed at all three soil depths measured. The other sites, while varying greatly in organic C content, did not exhibit significant differences in microbial activity. It was likely this site had increased microbial activity because it had been plowed more recently (in the current year of sampling) compared to the 1 year plowed pasture site.

In the loamy sand soil, there was some differences in microbial activity between management systems that differed between the soil depths (Table 8), but these differences did not correspond to difference observed in the organic C levels (Tables 2-7). At the 0-5 cm (0-2 in) depth, little difference was observed between the management systems, with the only significant differences observed between the permanent pasture being higher compared to the plowed pasture, the conservation tillage, and the forested soil. At the 5 to 10 and 10 to 15 cm (2-4 and 4-6 in) depth, microbial activity was significantly

Table 8. Effect of land management system on quantity of formazan from dehydrogenase assay in the 0-5, 5-10 and 10-15 cm depth increments.†

Soil type History	0-5 cm	5-10 cm	10-15 cm
	(µg g^{-1})		
Urbo Clay Loam			
Forested	2.1 a	1.5 a	1.4 a
Pasture - Permanent	2.4 a	1.6 a	1.3 a
Plowed 1 yr	2.9 a	1.3 a	1.2 a
Plowed 2 yr	8.7 b	4.7 b	1.8 b
Blanton Loamy Sand			
Forested	1.6 b	3.0 a	2.5 a
Pasture - Permanent	2.5 a	1.3 b	1.3 b
Plowed 2 yr	1.5 b	1.0 b	0.9 c
Conservation Tillage	1.5 b	1.4 b	1.4 b
Weedy-fallow	2.3 ab	1.5 b	1.5 b
Weedy-fallow - plowed	1.8 ab	1.6 b	1.2 bc

† Values represent means of 4 replicates. Means within a column (within a soil type) followed by the same letter do not differ significantly (0.05 level).

higher in the forested site compared to the other sites. This was likely due to increased levels of soil microorganism populations corresponding to deeper rooting in the forest and increased organic C content compared to the other loamy soil sites. Some differences were observed between the other management systems at the 10 to 15 cm (4-6 in) depth but, as stated earlier, these differences did not correspond to difference observed in the organic C levels (Table 8).

It is noteworthy that the highest microbial activity was measured in the site with the lowest organic C content in the clay loam soil, whereas the highest microbial activity was noted in the highest organic C content site in the loamy sand, at the 5 to 10 and 10 to 15 cm (2-4 and 4-6 in) depth (Table 8). Even in the loamy sand soil, however, the highest microbial activity did not correspond to the management systems with the highest organic C content at any soil depth. The difference in microbial activity may have resulted from a decreased microbial populations in one case and increased microbial activity in the other. These observations indicate that while microbial activity may be a good indicator of changes in soil quality (Kennedy and Papendick, 1995) understanding of the dynamics of the systems will be needed for interpretation of microbial activity impact on soil quality.

Summary and Conclusions

The results from this study indicate that the vulnerability of soil to lose sequestered C when cultivated depends on the soil type. In this study, clay loam soil had a much greater potential to sequester C compared to loamy sand soil. However, clay loam soil was more vulnerable to losing a large part of the sequestered C rapidly (55% after 2 years of cultivation). Carbon sequestration in clay loam soil was not impacted by conversion to permanent pasture compared to forest. In loamy sand soil, differences in C sequestration potential may increase with conversion to conservation tillage (or weedy-fallow) < pasture < forest management. However, no significant difference was immediately observed in the first year from plowing the loamy sand soil.

Endnote

Names are necessary to report factually on available data: however, the U.S. Department of Agriculture (USDA) neither guarantees nor warrants the standard of the production, the use of the name by USDA implies no approval of the product to the exclusion of others that may be suitable.

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