INCREASING BELOW-GROUND CARBON SEQUESTRATION WITH CONVERSION OF AGRICULTURAL LANDS TO PRODUCTION OF BIO-ENERGY CROPS*

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ABSTRACT

At three locations in the south-eastern United States, researchers have been quantifying differences in water and soil quality, run-off, and sediment transport with conversion from traditional agricultural crops to biomass crop production. After three growing seasons, soil quality improved and soil carbon storage increased on sites planted to short-rotation woody species (sweetgum, *Liquidambar styraciflua* L.; sycamore, *Platanus occidentalis* L.; and cottonwood, *Populus deltoides* Marshall), and a herbaceous species, (switchgrass, *Panicum virgatum* L.) when compared with agricultural crops (corn, *Zea mays* L., for grain or silage; and cotton, *Gossypium hirsutum* L.). The greatest increases in carbon sequestration under the woody and herbaceous biomass crops occurred in the upper 10 cm of the soil profile. At the Alabama site with conversion from traditional corn production to biomass crops, soil carbon increased under switchgrass, no-till corn, and sweetgum with a cover crop (tall fescue, *Festuca eliator* Schreber) established between the rows. The sweetgum treatment without a cover crop between rows showed a 6% decrease in soil carbon storage over the first 3 years. All three woody crops (sweetgum, sycamore, and cottonwood) sequestered considerable organic matter (OM) below-ground primarily as stumps and large roots and to a lesser extent as fine roots. At the Tennessee site, the below-ground OM associated with the sycamore was approximately 7.4 Mg/ha and at the Mississippi site 6.6 Mg/ha after 3 years of growth. Stumps and large roots contributed approximately 79% and fine roots 21% of these totals. At the Alabama site, the slower growing sweetgum had contributed only 1.8 Mg soil organic matter/ha after 3 years of growth. These plot-scale comparisons of the intensively managed biomass crop and traditional agricultural crops show that biomass crops can contribute to increasing below-ground carbon sequestration. The extent and timing of this sequestration is dependent on the individual growth characteristics of the different woody and herbaceous crops and the management practices employed.

Keywords: soil carbon; carbon changes; environmental effects; soil physical changes; biomass crops; short-rotation crops; herbaceous crops.

INTRODUCTION

Executive Order 13134 which was issued by President Clinton on 12 August 1999 (Federal Register 1999) calls for tripling United States energy production from renewable resources to 6 quads of primary energy by 2030. As a consequence, the role of alternative energy feedstocks, including dedicated energy crops and residues, takes on increased importance. Dedicated herbaceous and short-rotation woody energy crops, as well as residues, have the potential to provide significant feedstocks to support a viable biomass-to-bio-energy industry and provide biobased products such as gums, resins, oils, and fatty acids. In addition, woody crops can substantially contribute to fibre production thereby reducing demands on native forest resources. Approximately 6.9 million hectares will be required to meet the dedicated feedstock demands of 79 million dry tons for production of 1.25 quads of energy (Walsh in press). With this substantial land use requirement, we must determine the environmental aspects of their production to identify benefits and mitigation measures required to ensure sustainable production of these crops. Demonstration of sustainable production will be required to ensure acceptance by producers, the general public, and environmental groups. Large-scale production of bio-energy crops on erodible or more marginally productive lands can provide soil and water quality benefits in addition to being a source of dedicated feedstocks for energy (Grigal & Berguson 1998; Smith 1995). Use of erodible and less productive lands for cultivation of dedicated biomass feedstocks can help minimise potential land use competition between these feedstocks and traditional agricultural crops. The potential for environmental impacts from site preparation and production on these lands is greater and the yields less than would occur on more productive agricultural lands. The greatest gains in soil quality and carbon storage with conversion to biomass crops are expected to occur on lands that were previously in agriculture, were barren (Smith 1995), or were degraded (Lal *et al.* 1998).

Here we define parameters of soil quality as those which relate directly to either (1) the productivity of crops or plant communities, or (2) the movement of substances off-site which have the potential to degrade either surface or sub-surface waters. Examples of soil quality parameters include those that affect the retention of nutrients, organic matter, and soil on site, as well as soil aeration, penetrability of the soil by roots, and infiltration capacity. These parameters in turn potentially affect water availability to plants, surface runoff, erosion, and nutrient removal.

The overall goal of this research was to determine changes in water quality, soil physical and chemical properties, runoff, and sediment transport during the early years of establishment of biomass crops on agricultural croplands compared with traditional agricultural crops. The locations of the sites chosen for the comparisons are within regions of the Tennessee Valley with identified potential for economical yields of biomass crops as energy feedstocks (Graham & Downing 1995). Preliminary results of the surface water and nutrient transport components of this study have been reported by Thornton *et al.* (1998) and Tolbert *et al.* (1997, 1998). This paper focuses on changes in soil physical factors and below-ground carbon sequestration with conversion of agricultural lands to biomass crop production.

METHODS

On three sites in the Tennessee Valley, replicated 0.5- to 1.2-ha plots were established on sites that historically had been in conventional tillage for corn, soybeans, or cotton. The individual plots were enclosed within earthen berms to exclude off-site surface runoff; then the plots were prepared and planted to the agricultural or biomass crop selected for the particular location. Each plot was instrumented with v-notched weirs and ISCO flow-proportional samplers. Two pan lysimeters per plot were installed below the water table to monitor subsurface movement of nutrients for long-term monitoring to quantify differences in runoff as well as sediment and nutrient transport. Sweetgum with a fescue cover crop approximately 2 m wide between 3-m rows, sweetgum without a cover crop, switchgrass, and no-till corn for grain plots were established at the site in northern Alabama (AL). Sweetgum were established on 1.5 × 3 m spacing. Eastern cottonwood was established in western Mississippi (MS) on 2 × 3.3 m spacing for comparison with conventional-till cotton, and American sycamore was established at 2 × 3.3 m spacing in western Tennessee (TN) for comparison with no-till corn for silage. At the TN site, existing 12-year-old sycamore were included in the soil quality change comparisons. The AL site is on Decatur silt loam soil, the Mississippi site is on a Bosket silt loam soil, and the TN site is on a Memphis-Loring silt-loam intergrade. Soil physical characteristics (bulk density, penetration resistance, infiltration, and aggregate stability) were measured at each site in 1995 prior to crop establishment and again at the end of the third growing season (1997) to determine changes in soil quality over time. More detailed descriptions of the sites, methods, and results of water quality monitoring have been given by Joslin & Schoenholtz (1998), Thornton *et al.* (1998), and Tolbert *et al.* (1998).

Below-ground biomass was determined for each tree crop at the end of the third growing season. For each tree-crop treatment, six stumps and those roots extracted with the stumps out to 25 cm were weighed, dried, and re-weighed to determine organic matter (oven-dry mass) content. At MS, the carbon content was determined by combustion at 600°C for 6 hours. At TN, the organic matter was measured with a LECO carbon analyser. Beyond 25 cm from the stump, replicate 10-cm root cores were taken at depths of 0–1.25 cm, 1.25–7.5 cm, 7.5–15 cm, 15–30 cm, and 30–60 cm to determine root biomass for both tree and switchgrass crops. Soil carbon was determined for both the biomass and agricultural crops at each of the three sites. At the AL site, additional soil cores were taken to a depth of 60 cm from both tree crops and no-till corn in 1999 prior to the beginning of the fifth growing season. The samples were analysed in 10-cm increments to determine the carbon distribution and to compare the longer-term effects of the cover crop on carbon storage under the sweetgum treatments. Data were analysed using ANOVA and Duncan's multiple range test to separate statistically significant treatments.

RESULTS AND DISCUSSION

Soil physical parameters have been shown to change following establishment of biomass crops at all three research sites (Tolbert *et al.* 1998, 1999). Here we present selected examples from the three sites to illustrate changes that have occurred in soil physical parameters over the first 3 to 4 years of the biomass crop rotation.

At the MS site, aggregate stability within the upper 3 cm of the silt loam soil converted to cottonwood production increased from 2.8% to 5.6% within 3 years after tree crop establishment (Pettry *et al.* 1997). There was significantly greater ($p<0.05$) aggregate stability under the 12-year-old sycamore at the 0–3 and 3–6 cm depths (1.44 and 1.60 mm MWD (mean weight diameter), respectively) than under the 3-year-old sycamore (0.92 and 1.05 mm MWD) and no-till silage corn (0.96 and 1.15 mm MWD) at the TN site (Houston *et al.* 1997). After 4 years of growth, aggregate stability had significantly increased on the no-till corn plots but not on the young sycamore plots. The difference between the response of the sycamore and no-till corn at the TN site is thought to be the result of 4 years of continuous no-till cultural practices and the more extensive root system developed by the no-till corn with an annual winter wheat cover crop compared with the more spatially restricted, less fibrous root system of the young sycamore (Tyler *et al.* 1999).

At the MS site, both penetration resistance and bulk density decreased with time on the cottonwood plots compared with the cotton plots. After the first growing season, the soil traffic pan (initially at a depth of 15 to 30 cm) was not evident under the cottonwood but persisted under the cotton rotation. The penetration resistance dropped by half (from 3.0 to 1.5 MPa) in the upper 10–20 cm and the bulk density from 1.46 to 1.29 Mg/m^3 over the 3-year rotation (Pettry *et al.* 1997). While bulk density generally decreased at the TN site, significant changes occurred only within the upper 30 cm for 12-year-old sycamore plantings (1.25 Mg/m^3 compared with 1.42 Mg/m^3, $p<0.05$). There were no significant overall changes in the bulk density within the no-till corn plots after the first 3 years of growth. However, under the young sycamores, the bulk density at a depth of 0–3 cm showed a significant decline from 1.40 to 1.17 Mg/m^3 ($p<0.05$) from years 1 to 3 (Houston *et al.* 1999). At the 0–3 cm depth, bulk densities under the 3-year-old sycamore (1.17 Mg/m^3) and the 12-year-old sycamore (1.18 Mg/m^3) were not significantly different ($p<0.05$) but were significantly different from the no-till corn at the same depth(1.34 Mg/m^3). Further data analyses in progress will allow us to determine how bulk densities vary with depth and with distance from the tree centre on the tree crop plots at the AL site.

At the TN site, within 25 cm of the stem centre the greatest organic carbon increases were due largely to storage of carbon in the living stumps and large roots (Fig. 1). Beyond 25 cm, soil organic matter was the greatest contributor to the overall carbon storage below-ground. At the MS site, the soil carbon (excluding stumps and large roots) under cottonwood was 6.8 Mg/ha. With stump and coarse roots included, the below-ground biomass was approximately 8.2 Mg/ha. During the first growing season, the cottonwood, which were established from cuttings, did not develop a tap root but formed a dense horizontal root system. This root system extended across the 3.6 m distance between rows, most notably at a depth of 10 to 25 cm. Approximately 60% of the soil organic carbon under the cottonwood occurred in the upper 30 cm, although small roots extended to depths of >1 m (Pettry *et al.* 1997). The greater distribution of cottonwood roots in the upper 30 cm is consistent with distributions found to this depth by G.A.Tuskan (pers. comm.) for cottonwood (70%), sweetgum (71%), and sycamore (59%) grown in short-rotation plantings in South Carolina.

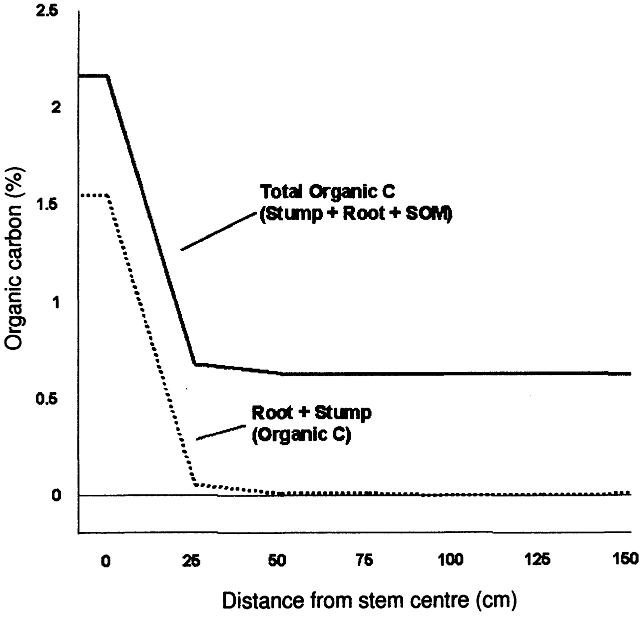

FIG. 1—Contribution of the different below-ground tree crop components to carbon storage—an example from the TN site after 3 years of growth. Stumps and large roots were the greatest contributors within 25 cm from the stem centre. Soil organic matter was the primary contributor beyond 25 cm.

Sycamore and no-till corn established on former traditional agricultural lands at the TN site increased soil carbon in the upper 15 cm by 27% and 34%, respectively, by the end of the third growing season. The increase in soil carbon storage under the sycamore was approximately 1.3 Mg/ha annually. This increase is similar to those found by Hansen (1993) for soil carbon accretion rates under hybrid poplar in the north-central states. Soil carbon under cottonwood at the MS site increased by 19% by the end of the third growing season; there was no change in soil carbon for the cotton plots (Fig. 2). The increase in soil carbon on the plots converted from traditional agricultural crops to no cultivation is consistent with the projections made by Smith (1995) that reforestation of agricultural lands could increase carbon sequestration in soils.

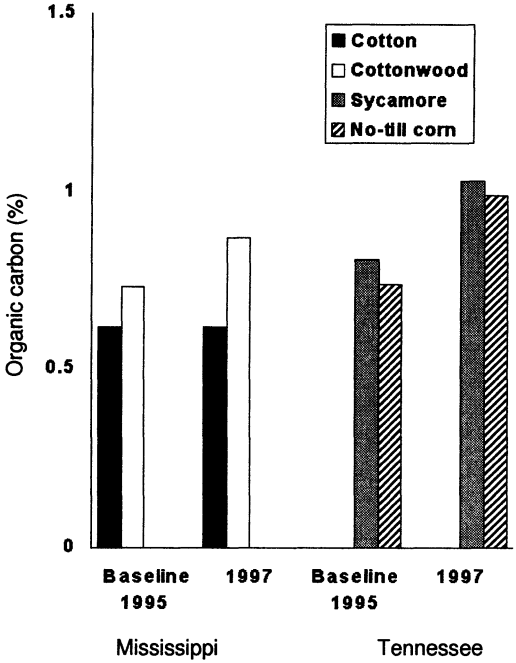

FIG. 2–Comparison of soil carbon on agricultural sites in 1995 prior to establishment with carbon production of tree crops, no-till corn, and cotton after 3 years of biomass crop growth. Sampling depth at MS was 0–15 cm and at TN 0–30 cm.

There was a significant increase ($p<0.02$) in soil carbon, particularly in the upper 2.5 cm, under switchgrass, sweetgum with a cover crop, and no-till corn over a 3-year period at the AL site. By contrast the plots of sweetgum without a cover crop actually lost 6% of the baseline carbon within the upper 15 cm over the same period (Fig. 3); most of the loss occurred in the 7.6–15 cm depth. Statistical analyses (Duncan's multiple range test) showed that the baseline (1995) and sweetgum treatments without a cover crop were not significantly different ($p<0.05$). After 4 years of growth, below-ground carbon storage within the upper 60 cm was 3.7 and 3.9 kg/ha for sweetgum with cover and no-till corn, respectively, and 2.7 kg/ha for sweetgum without a cover crop (Fig. 4). The loss of carbon by sweetgum without a cover crop treatment is consistent with Hansen's (1993) early studies of short-rotation woody crops, where he determined that carbon losses occurred initially with establishment of hybrid poplar in Minnesota. The losses in soil carbon occurred as the result of maintaining surface soils in a clean-tilled state to minimise weed competition with the trees and as a result of carbon mineralisation with continued soil exposure. After this initial decrease in soil carbon storage, soil carbon was projected to increase over the next 12 years

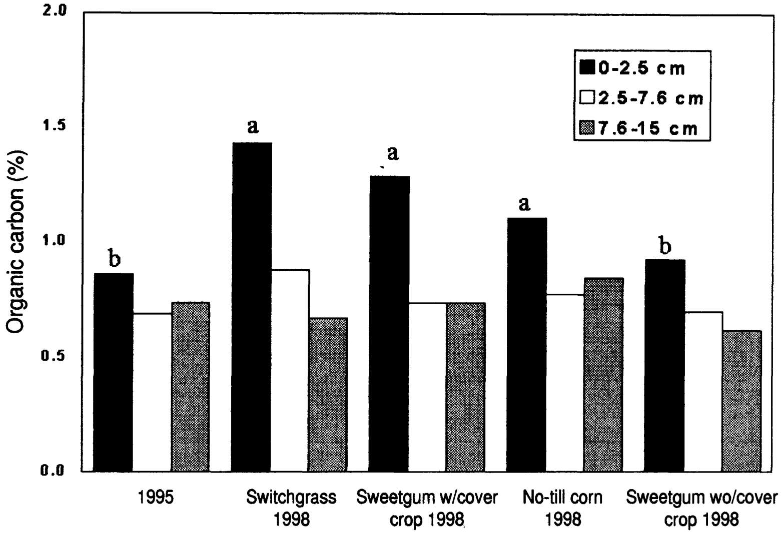

FIG. 3–Soil carbon changes after 4 years on an agricultural site in northern Alabama with conversion to switchgrass, sweetgum with a cover crop, and no-till corn for grain. Treatments with the same letter were not significantly different ($p < 0.05$). Comparisons for the 0–15 cm depth showed significant increases for switchgrass, sweetgum with a cover crop, and no-till corn. The greatest increases occurred within the upper 2.5 cm.

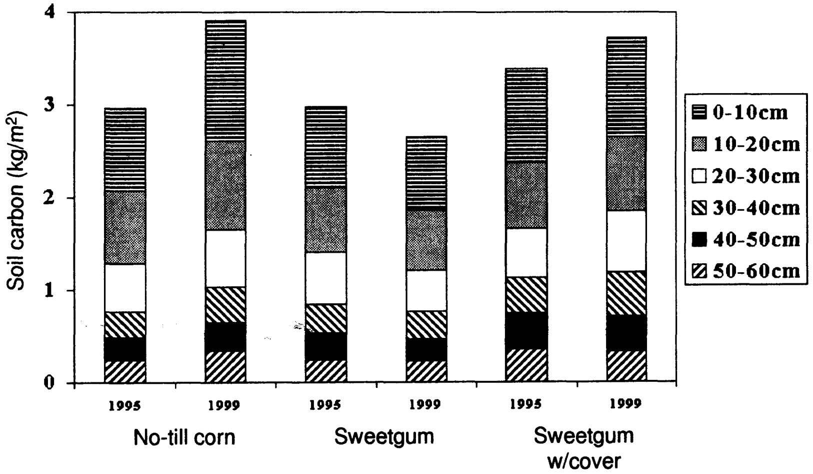

FIG. 4–Comparison of carbon storage (kg/ha) within the upper 60 cm by no-till corn and sweetgum, grown both with and without a cover crop on an agricultural site in northern Alabama.

of a tree crop rotation (Hansen 1993). Most of the increased carbon storage was expected to occur in the upper 30 cm.

The potential for switchgrass to provide environmental and soil quality benefits, is shown by differences in runoff volume and sediment transport compared with no-till corn at the AL site. Comparisons showed an increased percentage of soil carbon on the switchgrass plots at the AL site (Fig. 3). This increase with switchgrass establishment has been found across a wide range of sites from Texas through Virginia when compared with fallow plots and initial samples (McLaughlin & Walsh 1998). Garten & Wullschleger (1999) found significantly ($p \leq 0.05$) more coarse root (>2 mm) carbon under some of these switchgrass plantings and nearby forested sites than under tall fescue, corn, or native pastures of mixed grasses; however, soil organic carbon did not differ across comparisons.

Johnson *et al.* (1995) identified the need to determine the effects of management practices and soil properties on soil carbon storage in intensive production systems. This three-site study in the south-eastern United States has provided the opportunity to begin to quantify some of these differences. The data from the three south-eastern sites are showing many benefits for soil physical and chemical characteristics. These benefits accrue largely from adoption of conservation tillage practices for biomass, e.g., incorporating cover crops on woody crop sites, establishment of perennial crops, and no-till agricultural crop production on traditionally cultivated agricultural lands. K.Paustian, E.T.Elliott, G.Bluhm, and T.Kautza (unpubl. data) concluded that adoption of no-till crop production can play a major role in increasing soil quality and carbon storage. They identified increases in carbon sequestration in Iowa of 0.89 million tons per year from adoption of no-till production and 0.84 million tons per year from taking erosive farmlands out of production.

Additional benefits from production of perennial biomass crops result from eliminating the annual cycle of crop establishment and from the build-up and incorporation of a surface litter layer over time. The contribution of changes in management practices and the accumulation and incorporation of leaf litter into the shallow soil profile was particularly true for cottonwood and sycamore during the first few years of the tree crop rotation and with switchgrass establishment. With soil surface cover established, sediment losses (Fig. 5) overall were less from the biomass crops and no-till corn than from the conventional agricultural crop (cotton). Runoff from the sycamore and the no-till corn at the TN site was not very different (Fig. 6) and, as would be expected, generally tracked precipitation in its response. Data show that the "flashiness" of runoff in response to rainfall events was a major contributor to both sediment (Fig. 5) and nitrate runoff (Fig. 7). The extensive litter generated by the cottonwood and the recalcitrant litter provided by the sycamore in the first year provided extensive soil cover and runoff protection at these two sites. At the AL site, the slower-growing sweetgum did not provide a substantial litter soil cover until well into the third year of growth.

The AL site has provided the opportunity to begin to determine how management practices such as establishing cover crops between rows of intensively managed tree crops can contribute to site quality and below-ground carbon sequestration. Sweetgum established and maintained without a cover crop at the AL site released approximately the same amount of sediment as the conventionally tilled cotton at the MS site. By contrast, the sediment transport from the sweetgum established and maintained with a cover crop strip between rows was not different from the no-till corn or the switchgrass after its initial year of establishment. Quantifying changes in soil stability with conversion of agricultural lands to biomass crop production can provide a framework for ensuring retention of more organically

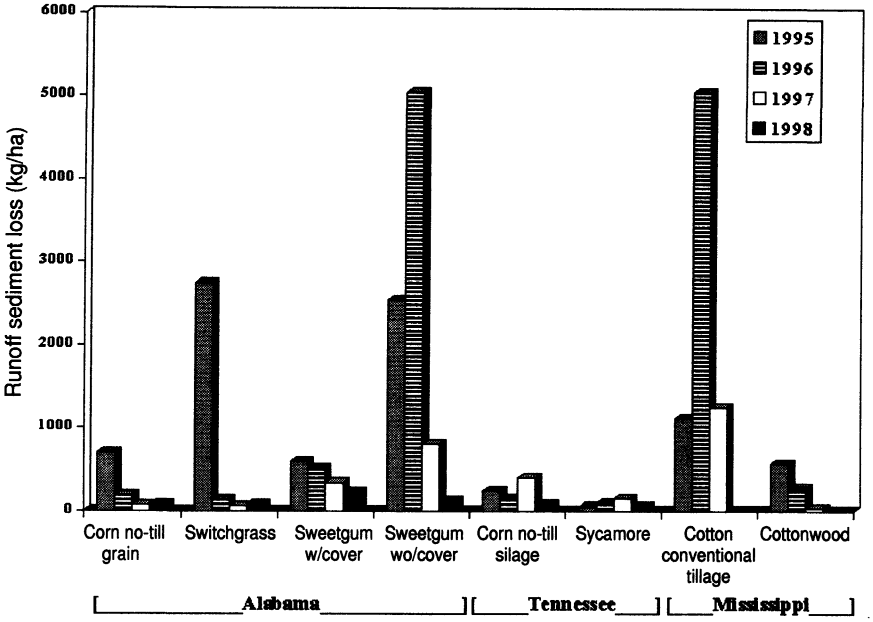

FIG. 5—Annual differences in sediment losses from the biomass and agricultural crops across the three research sites.

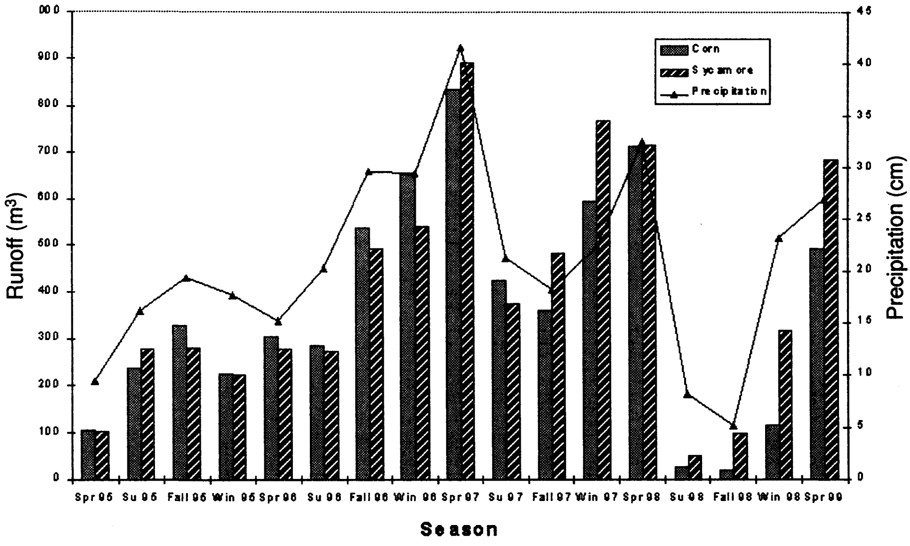

FIG. 6—Comparisons of runoff in response to precipitation from the sycamore and no-till corn for silage crops from time of initial establishment in spring 1995 through spring 1999 at the Tennessee research site.

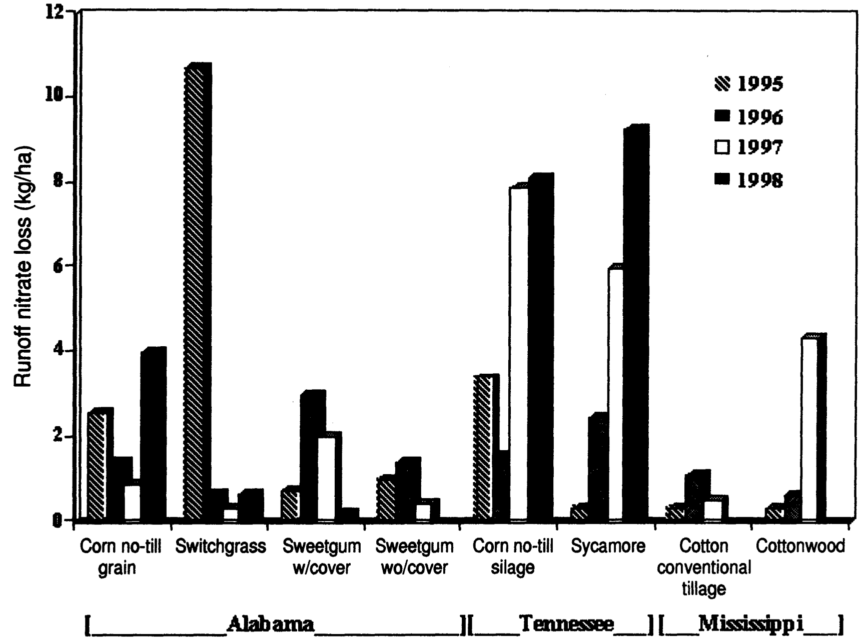

FIG. 7–Annual differences in nitrate losses from the biomass and agricultural crops across the three research sites.

rich surface soils, nutrients, and organic matter derived from breakdown of litter. The ability to maintain and incorporate carbon into the soil profile can increase soil carbon content and storage on former agricultural sites.

The data presented above quantify initial improvements in soil quality and soil carbon storage from establishing a fescue cover crop between rows of sweetgum at the AL site. Malik *et al.* (1996) in a companion study at this site addressed the effectiveness of different cover crops (crimson clover (*Trifolium incarnatum* L.), sericea lespedeza (*Lespedeza cuneata* Dumont), winter rye (*Lolium multigeonum* Lam.), and fescue (*Festuca eliator*)) established at two widths (1.2 and 2.4 m) for erosion protection while identifying the effect on sweetgum productivity. Initial results showed that the four cover crops provided erosion protection. During early establishment, there was no effect of cover crop or cover width on productivity. The researchers are currently measuring growth at the end of the fifth growing season to determine if there are longer-term productivity impacts. With both studies at this site, following the different treatments through a full rotation will determine the long-term effects of cover crops on both productivity and below-ground carbon storage.

CONCLUSIONS

Conversion of traditional agricultural lands to production of short-rotation woody and herbaceous crops as energy feedstocks is showing considerable potential to sequester carbon in the below-ground components of these crops. Crop rotations of 5 to 20 years for both woody and perennial herbaceous crops offer the potential to provide longer-term storage of soil carbon below-ground. Data from three south-eastern sites show the value of soil cover provided by switchgrass, sweetgum with a cover crop, no-till corn, sycamore, and cottonwood beyond initial years of establishment. The conversion from conventional-till agriculture to no-till agricultural crop and biomass crop production, establishment of a cover crop for erosion control, and the development of extensive root systems under the perennial biomass crops appear to be major factors accounting for the increasing carbon sequestration. Questions still to be considered are how the vertical distribution of soil carbon within the soil changes with time, the duration of the below-ground carbon storage, and the fate of the sequestered carbon with conversion of sites back to agricultural crop production.

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