Conversion from a Sycamore Biomass Crop to a No-till Corn System: Effects on Soils

Warren D. Devine,* Michael D. Mullen, Donald D. Tyler, Allan E. Houston, John D. Joslin, Donald G. Hodges, Virginia R. Tolbert, and Marie E. Walsh

ABSTRACT

Agricultural lands may be used to produce short-rotation woody crops (SRWCs) for fuel or fiber, but the effects of SRWCs on soils are poorly understood. In this study, a SRWC was integrated with an annual row crop system in a row crop–SRWC–row crop rotation. The objective was to document the effects of the woody crop on soil total C, N, inorganic N, and aggregate stability after the site was returned to row crop production. Soybean [*Glycine max* (L.) Merr.] was followed by 4- and 5-yr rotations of American sycamore (*Platanus occidentalis* L.), followed by no-till corn (*Zea mays* L.) (SY4C and SY5C, respectively). Continuous row crops (soybean converted to corn) served as a control (SBC). Four rates of broadcast NH_4NO_3 were applied to corn. The study was in southwestern Tennessee on a Memphis-Loring silt loam intergrade (fine-silty, mixed, active, thermic Typic Hapludalfs–fine-silty, mixed, active, thermic Oxyaquic Fragiudalfs). During 3 yr of post-sycamore corn production, increases in soil total C concentration below a 2.5-cm depth were attributed to the sycamore crop. After fertilization of first-year corn at 73 and 146 kg N ha^{-1}, soil inorganic N concentrations were lower in the SY4C than the SBC system from 0 to 2.5 cm. Mean weight diameter (MWD) of water-stable soil aggregates at depths of 2.5 to 15 cm was greater for the SY4C than the SBC system. Four- and 5-yr sycamore rotations significantly affected chemical and physical properties of an agricultural soil.

Biofuels such as herbaceous and woody biomass crops are a renewable alternative to fossil fuels. Because the amount of land required to produce biomass crops for a developed bioenergy industry would be substantial, agricultural land could make up a major portion of this land base (Walsh et al., 2000). Establishing perennial biomass crops, such as SRWCs, which are also used to produce wood fiber, has been shown to improve agricultural soils by lowering bulk density and reducing sediment in runoff (Thornton et al., 1998; Tolbert et al., 1999). A limited number of studies have examined the effect that converting croplands or grasslands to SRWCs has on soil C (Hansen, 1993; Grigal and Berguson, 1998; Mehdi et al., 1999; Tolbert et al., 2000). However, there is still a need for further quantification of the aboveground and especially the belowground C fluxes in SRWC systems.

Residues from SRWCs can affect soils differently from residues from annual row crops. A major source of litter in a SRWC system is the turnover of fine roots (Friend et al., 1991). However, the effects of root decomposition on an undisturbed soil environment are difficult to quantify (Waird, 1974; Urquiaga et al., 1998). The woody root residues from SRWCs have a high C/N ratio and therefore have the potential to cause immobilization of N during the microbial decomposition process. An increase in root N concentration, likely due to microbial immobilization, was reported during decomposition of fine tree roots (Arunachalam et al., 1996). Nitrogen immobilization after the addition of high C/N plant residues to agricultural soils is well documented (Schomberg et al., 1994), and the addition of woody residues to agricultural soils also has been shown to cause significant N immobilization (Beauchemin et al., 1990; N'dayegamiye and Dubé, 1986; Lalande et al., 1998). The effect of decaying tree roots from a harvested SRWC on soil plant-available N is not well understood.

Soil aggregate stability, or the ability of soil aggregates to resist breakdown, is a measure of soil structure that affects aeration, infiltration rate, and resistance to erosion (Kemper and Rosenau, 1986). With a few exceptions, increased soil organic C is positively correlated with increased aggregate stability (Tisdall and Oades, 1982). While this correlation may be due to amounts of organic binding agents in the soil, aggregation itself can protect soil organic C from oxidation by making it less accessible to microbes (Van Veen and Kuikman, 1990). Fungi play a major role in decomposition of high-C woody and herbaceous residues (Kaarik, 1974), and fungal hyphae are important in the formation of soil aggregates (Beare et al., 1997; Tisdall and Oades, 1982). In recent years, studies have been established to investigate the effects of SRWCs on soil physical properties including aggregate stability (Thornton et al., 1998; Tolbert et al., 1999; Bandaranayake et al., 1996).

Although several studies have shown positive effects of establishing SRWCs on former agricultural soils, there is a lack of information on whether these soil improvements endure after a site is converted back to agricultural crop production. Conversion of land from SRWC production back to traditional row crop production is a realistic possibility given fluctuations in crop prices. Alternatively, a farmer could plan a row crop–SRWC–row crop sequence if there were sufficient evidence that significant improvements in soil quality

W.D. Devine, Olympia Forestry Sciences Lab., USDA Forest Service PNW Research Station, 3625 93rd Ave. SW, Olympia, WA 98512; M.D. Mullen, Dep. of Agronomy, Univ. of Kentucky, N-122 Ag. Sci. Ctr.-North, Lexington, KY 40546-0091; D.D. Tyler, West Tennessee Experiment Station, Univ. of Tennessee, 605 Airways Blvd., Jackson, TN 38301; A.E. Houston, Ames Plantation, Univ. of Tennessee, P.O. Box 389, Grand Junction, TN 38039; J.D. Joslin, Belowground Forest Research, 112 Newcrest Ln., Oak Ridge, TN 37830; D.G. Hodges, Dep. of Forestry, Wildlife & Fisheries, Univ. of Tennessee, P.O. Box 1071, Knoxville, TN 37901-1071; V.R. Tolbert and M.E. Walsh, Oak Ridge National Laboratory, P.O. Box 2008, MS-6422, Oak Ridge, TN 37831-6422. Received 3 Aug. 2002. *Corresponding author (wdevine@fs.fed.us).

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: ANOVA, analysis of variance; MWD, mean weight diameter; SBC, Soybean crop followed by corn crop; SRWC, Short-rotation woody crop; SY4C, 4-yr-old sycamore plantation followed by corn crop; SY5C, 5-yr-old sycamore plantation followed by corn crop.

would result from the SRWC. This study examines such a sequence, focusing on the conversion of a site from a woody biomass crop back to a row crop system. Preliminary results were reported by Devine et al. (2002a,b). The objective of the study was to document the residual effects of a sycamore biomass crop on soil total C, N, inorganic N, and aggregate stability after the site was converted to a no-till corn system.

MATERIALS AND METHODS

The study began in 1995 on the Ames Plantation in Fayette County, located in southwestern Tennessee (35° 08′ N, 89° 13′ W). Soils were a Memphis-Loring silt loam intergrade, formed in aeolian loess. Soil pH was 6.0 to 6.5. The study was analyzed as a completely randomized, split-plot design with a whole-plot factorial treatment arrangement and four replications. The whole-plot treatments were cropping system and N fertilization rate, and the split-plot treatment was sampling depth. The three cropping systems were: (i) soybean converted to sycamore in 1995 converted to corn in 1999 (SY4C), (ii) soybean converted to sycamore in 1995 converted to corn in 2000 (SY5C), and (iii) soybean converted to corn in 1999 (SBC; control treatment). Nitrogen fertilizer, in the form of NH_4NO_3, was broadcast at four rates (0, 73, 146, and 219 kg N ha^{-1}). No-tillage systems were used for all row crops.

A 0.6-ha section of a soybean field was planted with 1-yr-old American sycamore seedlings on a 1.5 by 3.0 m grid (2222 trees ha^{-1}) in February 1995. Approximately 640 sycamore trees were harvested in October 1998 after four growing seasons in the field, and an equal number were harvested in October 1999 after five growing seasons in the field (Table 1). At harvest, trees were cut as close to the ground as possible (approximately 2 to 5 cm from the soil) with chainsaws, and stumps were treated with glyphosate to prevent sprouting. After both the SY4C and the SY5C sycamore harvests, the same procedure was used to convert the site to corn production. Wheat (*Triticum aestivum* L.) was planted after sycamore harvest as a winter cover crop. Glyphosate [N-(phosphonomethyl) glycine; Roundup, Monsanto Co., St. Louis, MO] and atrazine (2-chloro-4-ethylamine-6-isopropylamino-S-triazine; Bicep II and AaTrex, Ciba-Geigy Corp, Greensboro, NC) were applied to the cover crop the following April. Sixteen plots, each 10.7 by 15.2 m, were then established on the site. Each plot encompassed approximately 35 sycamore stumps. The 16 plots consisted of four randomly assigned replications of the four N fertilization rates (Fig. 1). When the first set of post-sycamore plots (SY4C) was established in April 1999, a set of 16 plots was also established on the adjacent SBC treatment that had been in no-till soybean through 1998. After plots were designated, corn was planted over the sycamore stumps and lime was applied at a rate of 4.5 Mg ha^{-1}. Planting dates were 12 Apr. 1999, 21 Apr. 2000, and 30 Apr. 2001. Ammonium nitrate was broadcast on 3 May 1999, 4 May 2000, and 30 May 2001. Corn grain was harvested 2 Sept. 1999, 15 Sept. 2000, and 25 Sept. 2001. The SY4C and SBC cropping systems remained in corn for 3 yr (1999-2001), while the SY5C system was in corn for 2 yr (2000-2001).

Soil samples for chemical analysis were collected 22 Apr., 16 June, and 1 Dec. 1999 in the SY4C and SBC systems and 2 May 2001 in all three systems. Abnormally dry conditions prevented collection of soil samples in 2000. In 1999, April samples were collected 11 d before N fertilization, and June samples were collected 44 d after fertilization. May 2001 samples were collected 28 d before N fertilization. Soil samples for chemical analyses (n = 1920) were collected from four depths (0–2.5, 2.5–7.5, 7.5–15, and 15–30 cm). Each sample consisted of a composite of eight to ten soil cores (1.75-cm diam.) sampled with a steel soil probe. On SBC plots, samples were collected from two randomly chosen row middles. On SY4C and SY5C plots, each sample consisted of soil cores collected in a circular pattern around each of two randomly chosen stumps per plot. Two sampling circles per stump with radii of 5 and 37.5 cm were used. An exception was May 2001 when plots fertilized at 146 kg N ha^{-1} also had cores removed in circles with radii of 75 and 150 cm. For this set of samples taken at four distances from the stump, distance was analyzed as an independent variable. For all other analyses, data extracted from the samples taken 5 and 37.5 cm from the stumps were used to represent the SY4C and SY5C systems.

Fine organic particles (<2 mm) were not removed from soil samples before analyses. Soil samples were air-dried, ground to pass through a 250-μm sieve, and analyzed for total C and N by the dry combustion method (Matejovic, 1997) using a LECO CNS-2000 elemental analyzer (Leco Corp., St. Joseph, MI). Due to the acidity of the soil, most, but not all, soil C was assumed to be organic. During the course of the study, increases in soil total C were assumed to be increases in organic C since lime was not applied after soil sampling had begun. Concentrations of NO_3^- and NH_4^+ were measured

Table 1. Treatment and sampling activities for soybean–corn (SBC), 4-yr sycamore–corn (SY4C), and 5-yr sycamore-corn (SY5C) cropping sequences on a Memphis-Loring silt loam intergrade in southwestern Tennessee, 1998–2001.

	Year				
Activity	1998	1999	2000	2001	Notes
Harvest sycamore	Oct.	Oct.	–	–	Approximately 640 trees removed in each harvest.
Plant wheat cover crop	Nov.	Nov.	–	–	Cover crop used only on plots undergoing the sycamore to corn transition (SY4C in winter 1998-1999 and SY5C in winter 1999-2000).
Establish plots for corn	–	Apr.	Apr.	–	1999 plots were for SBC and SY4C systems; 2000 plots were for SY5C.
Plant corn	–	12 Apr.	21 Apr.	30 Apr.	Pioneer 3335 in 1999 and 2000; Dekalb DK697 in 2001. 76.2-cm row width.
Apply herbicide to cover crop	–	13 Apr.	10 Apr.	–	Glyphosate (Roundup) and atrazine (Bicep II and AaTrex).
Apply lime	–	14 Apr.	–	–	All plots received rate of 4.5 Mg ha^{-1}.
Sample soils for chemical analyses	–	22 Apr., 16 June, 1 Dec.	–	2 May	SBC and SY4C systems sampled in 1999. SBC, SY4C, and SY5C systems sampled in 2001.
Fertilize with NH_4NO_3	–	3 May	4 May	30 May	Applied to plots at four rates.
Sample sycamore roots	–	–	–	16 May	SY4C and SY5C systems sampled.
Sample soils for aggregate stability	–	16 June	–	–	SBC and SY4C systems sampled.
Harvest corn grain	–	2 Sept.	15 Sept.	25 Sept.	

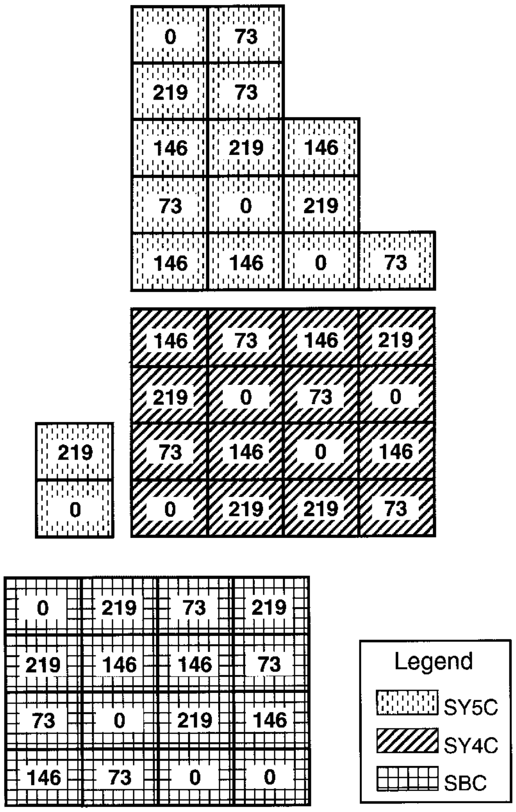

Fig. 1. Plot layout for soybean–corn (SBC), 4-yr sycamore–corn (SY4C), and 5-yr sycamore–corn (SY5C) cropping sequences. Numbers within plots indicate the rate of N (kg ha^{-1}) applied to corn.

by the modified indophenol blue technique described by Sims et al. (1995), following a 1 *M* KCl extraction.

Soil aggregate stability samples (n = 192) were collected 16 June 1999 from SY4C and SBC treatments. Samples were taken at two randomly selected locations per plot at three depths (0–2.5, 2.5–7.5, and 7.5–15 cm). Mean weight diameter of water-stable aggregates was determined by wet sieving after samples were wetted at atmospheric pressure (Kemper and Chepil, 1965). Sieve screen sizes were 2.0, 1.0, 0.5, and 0.25 mm.

The intact sycamore stumps and first-order roots that were impossible to sample with a soil probe were sampled by excavating one randomly chosen stump per plot (n = 16 for SY4C; n = 16 for SY5C) on 16 May 2001. A backhoe was used to excavate the stump as well as the soil within an approximate 1-m radius of the stump. The depths of these excavations were determined by the rooting depth and state of decomposition of the individual stump but were generally about 1 m. Intact root and stump fragments were sorted by hand from the excavated soil in the field. These fragments were cleaned, dried, weighed, subsampled, and analyzed for total C and N concentration by dry combustion (Matejovic, 1995).

Treatment effects on soils at each sampling date were evaluated with analysis of variance (ANOVA) using Proc Mixed in SAS (SAS Institute, Inc., 1997). Repeated measures analysis was not used due to within-subject variation from the uneven root distribution around each stump. Mean separations were performed with single degree of freedom orthogonal contrasts (Steel and Torrie, 1980). For all 1999 soils data, contrasts compared effects of SY4C and SBC cropping systems at each depth interval, except for the two deepest sampling intervals. Due to limited degrees of freedom, cropping system effects on the two deepest intervals were compared simultaneously.

Table 2. Analysis of variance for treatments affecting soil total C, N, and inorganic N (NO_3^- + NH_4^+) concentrations for a Memphis-Loring silt loam intergrade in southwestern Tennessee, May 2001.

Source of variation	Degrees of freedom	Total C	Total N	Inorganic N
Cropping system (C)	**1**	**NS**	*	**NS**
Stump distance (S)	**3**	**NS**	**NS**	**NS**
C × S	**3**	**NS**	**NS**	**NS**
Depth (D)	**3**	***	***	***
C × D	**3**	**NS**	**NS**	**NS**
S × D	**9**	**NS**	**NS**	**NS**
C × S × D	**9**	**NS**	**NS**	**NS**

*** Significant at the 0.05 probability level.**
***** Significant at the 0.001 probability level.**

Data from 2001 were analyzed in a similar manner, but separate contrasts compared the SY4C with the SBC system and the SY5C to the SBC system. Effects of decomposition time on root systems also were analyzed with ANOVA. A minimum confidence level of α = 0.05 was used in all analyses.

RESULTS

Soil total C, N, and inorganic N concentrations were not affected by sampling distance from sycamore stump, nor were there interactions between distance from stump and sampling depth or cropping system (Table 2). Estimates and data pertaining to the sycamore stumps and extractable roots appear in Table 3. Large differences between the 84- and 136-wk-old stump and root residues were observed for all parameters other than C concentration. These data were not used in conjunction with the soil data to estimate C and N pools since an undetermined fraction of the roots were extracted from a greater depth than the soil samples (below 30 cm).

Soil total C concentration varied significantly by depth at every sampling date, and in April 1999 and May 2001 there also was a significant cropping system × depth interaction (Table 4). This was due to higher concentrations of soil C at lower sampling depths for SY4C and SY5C systems compared with the SBC system (Fig. 2). At all four sampling dates, soil C was significantly greater in the sycamore cropping systems than in the SBC system from 7.5 to 30 cm. Significant differences in soil total C between cropping systems at the 0- to 2.5-cm depth occurred in June 1999 and May 2001. In June 1999, SBC soil C was less than that of SY4C; in May 2001, SBC soil C was significantly greater than that of SY4C and SY5C. Nitrogen fertilization rate did not affect soil total C concentration.

Table 3. Properties of 84-wk-old (SY5C) and 136-wk-old (SY4C) extractable sycamore roots and stumps on a Memphis-Loring silt loam intergrade in southwestern Tennessee.

	Cropping system	
Parameter	**SY5C**	**SY4C**
C concentration, g kg^{-1}	**428.3a†**	**422.1a**
N concentration, g kg^{-1}	**5.3a**	**9.3b**
C/N ratio	**85.3:1b**	**48.8:1a**
Estimated dry mass, Mg ha^{-1}	**4.95b**	**1.50a**
Estimated C content, Mg ha^{-1}	**2.12b**	**0.63a**
Estimated N content, kg ha^{-1}	**26b**	**14a**

† Within each row, values followed by the same letter are not significantly different (P > 0.05).

Table 4. Analysis of variance for treatments affecting soil total C, N, and inorganic N (NO_3^- + NH_4^+) concentrations for a Memphis-Loring silt loam intergrade in southwestern Tennessee.

Sampling date	Source of variation	Degrees of freedom	Total C	Total N	Inorganic N
April 1999	Cropping system (C)	1	***	***	**
	N fertilization (N)	3	NS	NS	NS
	C × N	3	NS	NS	NS
	Depth (D)	3	***	***	***
	C × D	3	***	***	NS
	N × D	9	NS	NS	NS
	C × N × D	9	NS	NS	NS
June 1999	C	1	***	NS	NS
	N	3	NS	NS	***
	C × N	3	NS	NS	NS
	D	3	***	***	***
	C × D	3	NS	***	***
	N × D	9	NS	*	***
	C × N × D	9	NS	NS	NS
December 1999	C	1	***	***	NS
	N	3	NS	NS	NS
	C × N	3	NS	NS	NS
	D	3	***	***	***
	C × D	3	NS	***	***
	N × D	9	NS	NS	NS
	C × N × D	9	NS	NS	NS
May 2001	C	2	NS	*	NS
	N	3	NS	NS	NS
	C × N	6	NS	*	NS
	D	3	***	***	***
	C × D	6	***	***	NS
	N × D	9	NS	NS	NS
	C × N × D	18	NS	NS	NS

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability levels.

Soil total N concentration was significantly affected by sampling depth at each sampling date. There also was a significant cropping system × depth interaction at each date. In April 1999, the SBC system had a higher soil total N concentration than the SY4C system at depths from 0 to 7.5 cm (Fig. 3). By December 1999, the SY4C system had higher total N than SBC from depths of 2.5 to 30 cm. In May 2001, the SBC system

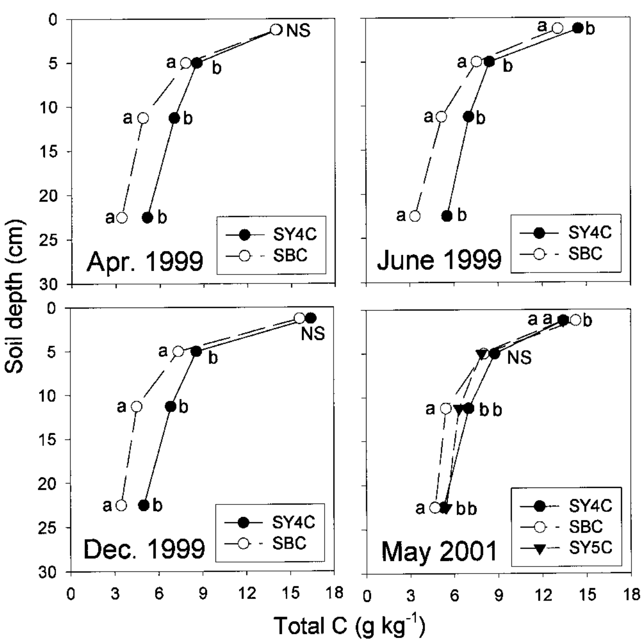

Fig. 2. Effects of soybean–corn (SBC), 4-yr sycamore–corn (SY4C), and 5-yr sycamore–corn (SY5C) cropping sequences on soil total C concentration for a Memphis-Loring silt loam intergrade in southwestern Tennessee. Four-year sycamore–corn sycamore crops were harvested in October 1998 and SY5C sycamore crops were harvested in October 1999. Within each depth, points with different letters are significantly different ($P < 0.05$).

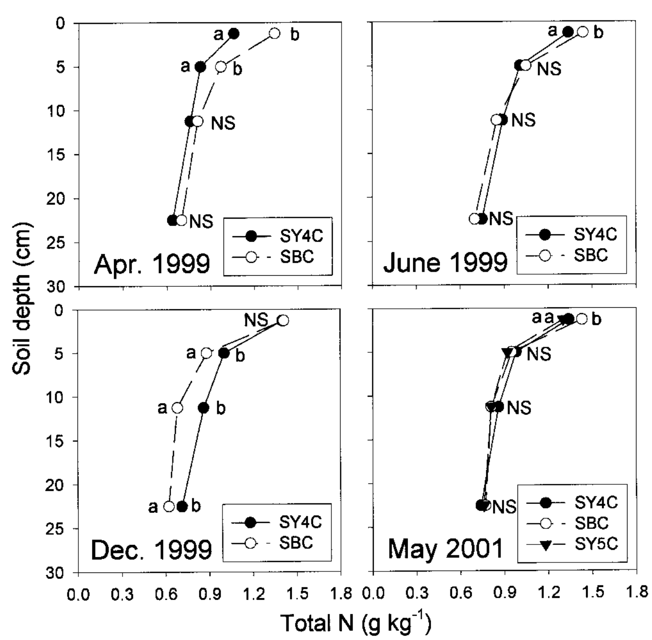

Fig. 3. Effects of soybean–corn (SBC), 4-yr sycamore–corn (SY4C), and 5-yr sycamore–corn (SY5C) cropping sequences on soil total N concentration for a Memphis-Loring silt loam intergrade in southwestern Tennessee. Four-year sycamore–corn sycamore crops were harvested in October 1998 and SY5C sycamore crops were harvested in October 1999. Within each depth, points with different letters are significantly different ($P < 0.05$).

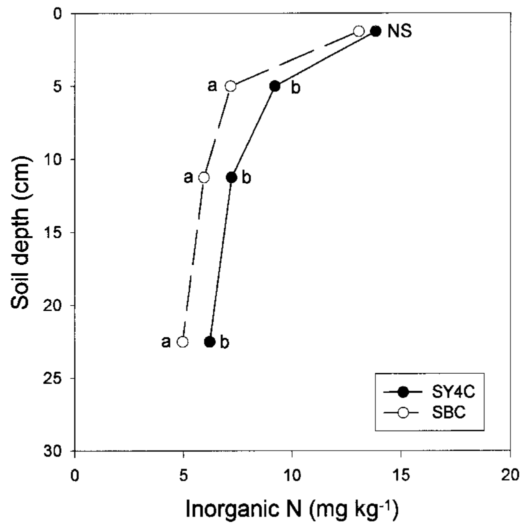

Fig. 4. Effects of soybean–corn (SBC) and 4-yr sycamore–corn (SY4C) cropping sequences on soil inorganic N (NO_3^- + NH_4^+) concentration for a Memphis-Loring silt loam intergrade in southwestern Tennessee, April 1999. Sycamore crops were harvested in October 1998. Within each depth, points with different letters are significantly different (P < 0.05).

had more total N than the sycamore cropping systems from 0 to 2.5 cm, but not at the lower depths. Nitrogen fertilization rate did not affect soil total N, although there were two interactions involving N fertilization. The interaction between N fertilization rate and depth that occurred in June 1999 reflected a higher soil total N from 0 to 2.5 cm on the plots receiving 219 kg N ha^{-1} fertilizer (data not shown). The May 2001 interaction between cropping treatment and N fertilization rate was due to a low total N concentration that occurred in the SY5C system at the fertilization rate of 73 kg N ha^{-1}.

Before the application of N fertilizer in the first season of corn, inorganic N was significantly greater under the SY4C system than the SBC system (P < 0.01; Fig. 4). At the next three (post-fertilization) sampling dates there was no overall effect of cropping system on soil inorganic N, although there were interactions between cropping system and sampling depth in June and December of 1999. On these dates, SBC systems had higher inorganic N concentrations at the 0- to 2.5-cm depth only (Fig. 5 and 6). No differences in soil inorganic N among cropping systems were observed in May 2001 at any sampling depth (Fig. 7). Rate of N fertilization significantly affected soil inorganic N concentration only at the June 1999 sampling date. There also was a significant fertilization rate × depth interaction at this time as N fertilization increased soil inorganic N to a greater extent at 0 to 2.5 cm than at lower depths.

While MWD of water-stable soil aggregates did not differ between cropping systems at a depth of 0 to 2.5 cm, the SY4C system had a larger MWD than the SBC system at depth intervals of 2.5 to 7.5 and 7.5 to 15 cm (Table 5). The difference was reflected by a greater fraction of macroaggregates larger than 2 mm under the SY4C system and a greater fraction of microaggregates (<0.25 mm) under the SBC system.

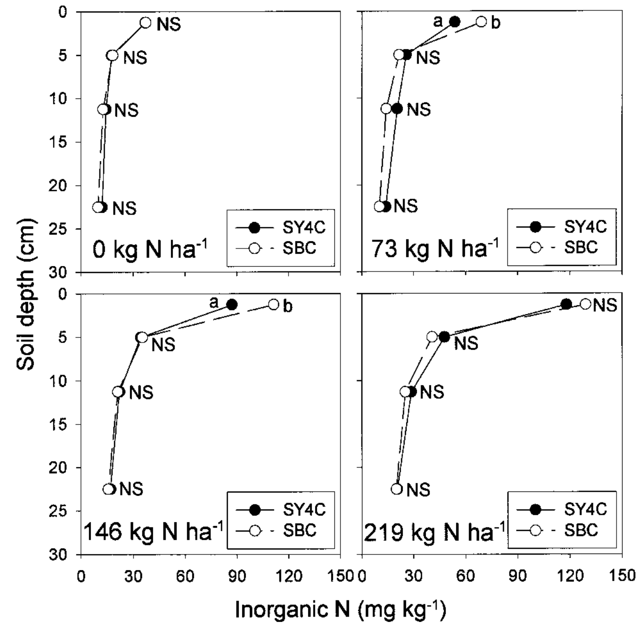

Fig. 5. Effects of soybean–corn (SBC) and 4-yr sycamore-corn (SY4C) cropping sequences on soil inorganic N (NO_3^- + NH_4^+) concentration at four rates of N fertilization for a Memphis-Loring silt loam intergrade in southwestern Tennessee, June 1999. Sycamore crops were harvested in October 1998. Within each depth, points with different letters are significantly different (P < 0.05).

DISCUSSION

The spatial uniformity of soil C and N concentrations observed in 2001 indicates that the effect of the woody crop rotation on the top 30 cm of soils was evenly distributed across the site. There was no evidence that the

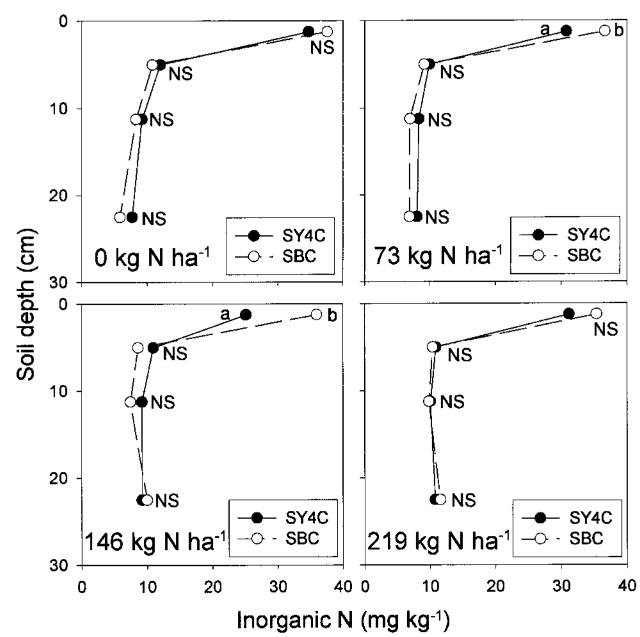

Fig. 6. Effects of soybean–corn (SBC) and 4-yr sycamore–corn (SY4C) cropping sequences on soil inorganic N (NO_3^- + NH_4^+) concentration at four rates of N fertilization for a Memphis-Loring silt loam intergrade in southwestern Tennessee, December 1999. Sycamore crops were harvested in October 1998. Within each depth, points with different letters are significantly different (P < 0.05).

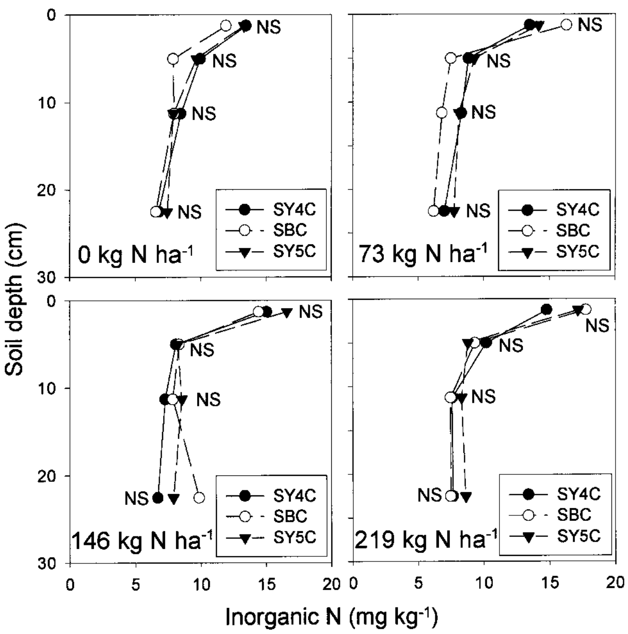

Fig. 7. Effects of soybean–corn (SBC), 4-yr sycamore–corn (SY4C), and 5-yr sycamore–corn (SY5C) cropping sequences on soil inorganic N (NO_3^- + NH_4^+) concentration at four rates of N fertilization for a Memphis-Loring silt loam intergrade in southwestern Tennessee, May 2001. Four-year sycamore–corn sycamore crops were harvested in October 1998 and SY5C sycamore crops were harvested in October 1999. Means were compared within each soil depth ($P < 0.05$).

cornrows that coincided with the tree stump rows were subject to different soil conditions than the cornrows located between the stump rows. The uniformity of the soil suggests that randomly located soil samples are adequate for similar SRWC studies. In contrast, Kaur et al. (2000) found that soil C and N decreased to a horizontal distance of 3 m from 6-yr-old hardwoods in an agroforestry system on a semiarid site in India. A higher initial concentration of soil C and N and closer tree spacing in our study may explain the difference in results.

Estimates of belowground C and N pools must include the tree stumps and intact first-order roots, which unless substantially decomposed, are unlikely to be sampled representatively by a soil probe. The three-fold difference in intact belowground dry biomass between the 84- and the 136-wk-old residues was clearly due in part to time since harvest but was also affected by the differences in stump size and root system development between the 4- and 5-yr-old trees. The decomposition process was considerably more advanced in the 136-wk-old root residues than in the 84-wk-old residues. This was evidenced by the higher N concentration and lower C/N ratio of the 136-wk-old SY4C roots. Although the estimated amount of N contained in extracted tree roots was quite small, many small roots and some larger ones were in advanced stages of decomposition and were therefore not extractable. Decomposed roots such as these were sampled by the soil probe and thus contributed to soil C and N concentrations.

Soil and vegetation disturbances have been suggested to cause soil C oxidation in the first years after establishment of SRWCs (Hansen, 1993; Grigal and Berguson, 1998). A study conducted in Minnesota and adjacent states that compared hybrid poplar (*Populus* sp.) plantations to grasslands and row crops documented net soil C losses among 4- to 6-yr-old plantations presumably due to the increased oxidation of organic C near the surface of the soil (Hansen, 1993). Another study in Minnesota found no significant change in soil C attributable to poplar plantations with an average age of 7 to 8 yr (Grigal and Berguson, 1998). The significant soil C increases associated with the SRWC in our study were probably due in part to a relatively low initial soil total C concentration of <8 g C kg^{-1} at a depth of 0 to 30 cm (Tolbert et al., 2000). The relative loss of soil organic matter due to disturbance was likely substantially lower in our study than in that of Hansen (1993), where soil C concentration was approximately 25 g C kg^{-1} (0- to 30-cm depth), and that of Grigal and Berguson (1998) where average soil C concentration was >35 g C kg^{-1} (0- to 25-cm depth). Alternatively, the relative contribution of root residues to soil total C may have been higher in our study than in the studies conducted by Hansen (1993) and Grigal and Berguson (1998). Three studies conducted on low-C soils (<10 g C kg^{-1}) in the southeastern USA found increases in soil C 3 to 4 yr after establishment of SRWCs (Tolbert et al., 1999). Garten (2002) observed a significant soil C increase at a depth of 10 to 30 cm but not at 0 to 10 cm for an 11-yr-old sweetgum (*Liquidambar styraciflua* L.) plantation in Tennessee.

Since the April 1999 soil C concentration at a depth of 0 to 2.5 cm was similar for SY4C and SBC soils, the effect of 4 yr of aboveground sycamore residue on soil C concentration was no different than that of 4 yr of residue from a no-tillage soybean system. A significant litter layer did not accumulate in the sycamore plantation until the end of the third year after planting. By that time there was sufficient litterfall and enough dropped limbs to trap abscised leaves, preventing them from being blown away during winter. The susceptibility of leaf litter to wind removal in this study may have been a result of the relatively small sycamore plantation within a much larger field. Wind removal would likely be substantially less in an operational-scale plantation.

Table 5. Mean weight diameter (MWD) and distribution among size classes of water-stable soil aggregates from soybean–corn (SBC) and sycamore–corn (SY4C) cropping sequences on a Memphis-Loring silt loam intergrade in southwestern Tennessee, June 1999.

	MWD		>2 mm		1–2 mm		0.5–1 mm		0.25–0.5 mm		<0.25 mm	
Depth	SBC	SY4C	SBC	SY4C	SBC	SY4C	SBC	SY4C	SBC	SY4C	SBC	SY4C
cm	mm		%									
0–2.5	2.42a†	2.49a	44.6a	46.1a	4.9a	5.0a	6.4a	6.9a	10.1a	9.8a	35.0a	33.7a
2.5–7.5	1.13a	1.56b	17.9a	26.7b	6.1a	5.9a	7.7a	8.1a	9.9a	10.4a	59.8b	49.9a
7.5–15	0.96a	1.30b	13.8a	20.8b	6.4a	6.6a	8.9a	8.9a	10.7a	10.9a	61.1b	54.1a

Cottonwood (*Populus deltoides* Bartr. ex Marsh.) plantations have shown significant surface litter accumulation, sufficient to affect soil hydrologic properties, in their second growing season (Mitchell, 1997). However, Hansen (1993) found no evidence of C accumulation from the trapping of wind-blown detritus in plantations of hybrid poplar (*Populus* sp.). The fact that most of the C increases observed in SY4C and SY5C soils occurred at the lower soil depths (2.5 to 30 cm) indicates that sycamore roots were a more important source of soil C than aboveground residues including leaves and dropped limbs.

Although the soil C increases 134 wk after sycamore harvest (SY4C vs. SBC system) occurred only between a depth of 7.5 and 30 cm, their significance suggests that the effect of a SRWC on soil C lasts at least 2.5 yr and perhaps much longer. The use of a no-till system in this study after the harvest of the SRWC likely helped to minimize oxidation of accumulated soil C. Since N fertilization rate had no effect on soil C in the SY4C system during the first 2.5 yr after sycamore harvest, any significant effect of repeated fertilization on the microbially mediated oxidation of sycamore roots will likely be either long-term or nonexistent. Halvorson et al. (1999) found a significant positive relationship between N fertilization rate and soil organic C, but this was due to cumulative increases in aboveground plant residues at higher N rates.

The effect of liming on soil total C concentration in this study was likely relatively minor since the single 4.5 Mg ha^{-1} lime application contained a small amount of C (540 kg ha^{-1}) compared with the soil total C pool (approximately 17 Mg C ha^{-1} from 0 to 15 cm). However, the effect of this added inorganic C on soil total C concentration would have been greatest at the June 1999 sampling date, $<$5 wk after lime was applied. Over time, H_2CO_3–C from the lime would have been released as CO_2, decreasing the fraction of lime-C relative to the soil total C pool. Since there was no decrease in soil total C between 1999 and May 2001, it is possible that a decrease in inorganic C was countered by a concurrent increase in the organic C fraction. Because lime was applied at a uniform rate to all study plots before the first soil sampling, it was not possible to test the effects of the lime on soil total C concentration or to measure the interactions between liming and the cropping system treatments.

The effect of fertilization on soil inorganic N concentration was observed at only one of the four soil sampling dates due to time of sampling relative to time of fertilization. In June 1999, only 6 wk after fertilizer application, soil inorganic N was strongly affected by fertilization, even at the lowest rate (73 kg N ha^{-1}). But by December 1999, there was no effect of fertilization rate on inorganic N. By that point, the fertilizer N had been removed from the inorganic fraction through plant uptake or microbial immobilization or was lost from the sampled profile. Similarly, in May 2001, 52 wk after the most recent fertilizer application, there were no differences in inorganic soil N among different fertilization rates. Since no post-growing season fertilization effects were observed in December 1999 or May 2001, none of the N fertilization rates were excessive.

The observed increase in total N for SY4C soils relative to SBC soils during 1999 was due to both an increase in SY4C soil N and a slight decrease in SBC soil N. The causes of these phenomena are not known. The differences in soil total N among cropping systems in the upper 2.5 cm of soils in May 2001 are small and may have no practical significance. The effect of fertilization on soil total N was expected to be minimal since the amount of fertilizer N added to the system (219 kg ha^{-1}) was relatively small in magnitude compared with the estimated soil total N pool (1970 kg ha^{-1} from 0 to 15 cm). However, the application of 219 kg fertilizer N ha^{-1} in April 1999 significantly increased soil total N from 0 to 2.5 cm in June 1999 (data not shown). This fertilization effect did not persist beyond the growing season, likely due to plant uptake and other losses of fertilizer N from the sampled profile.

Higher total N concentrations for SBC than for SY4C soils at shallow depths (0 to 7.5 cm) in April 1999 suggest greater N inputs from no-till soybean than from 4 yr of sycamore. A higher inorganic N concentration under the SY4C system in April 1999 may have been a result of increased microbial activity close to tree stumps. Samples taken 5 cm from stumps had a higher inorganic N content than those taken 37.5 cm away (Devine et al., 2002a). Kaur et al. (2000) found increased soil N mineralization rates in an agroforestry system compared with an agricultural system, possibly due to tree litter. Lower post-fertilization (June and December 1999) inorganic N at a depth of 0 to 2.5 cm under the SY4C system may have been due to immobilization of N during decomposition of shallow sycamore roots. Nitrogen immobilization was not detected in preliminary results from this study (Devine et al., 2002a).

In June 1999, the significant increases in soil C for the SY4C system relative to the SBC system were accompanied by significant increases in soil aggregate stability. The improved aggregate stability may have been due in part to the decomposing sycamore root residues. Seventy-six weeks after trees were harvested, the sycamore roots in this study had a C/N ratio of 80:1 (Devine, unpublished data, 2001). Addition of high-C residues to soil has been shown to cause increases in fungal populations and soil aggregate stability (Bossuyt et al., 2001; Lalande et al., 1998). In mostly undisturbed soil environments such as no-tillage systems (or the woody crop systems of this study) plant root C plays a much larger role than surface residue C in the formation of stable soil macroaggregates ($>$250 μm) (Gale et al., 2000). Since the increases in aggregate stability under the sycamore cropping system occurred at deeper sampling depths (2.5–15 cm) and not at the surface (0–2.5 cm), it is likely that the C from sycamore roots, rather than that from surface residues, was responsible for the increases.

The rotation length required for a woody biomass crop to improve soil structure has not yet been conclusively determined, although this study suggests that it may take as little as 4 yr. Mitchell (1997) found that soil aggregate stability 3 yr after cottonwood establishment was greater than that of a conventionally tilled cotton (*Gossypium hirsutum* L.) system. However, Houston and Tyler (unpublished data, 1997) found no increase in soil aggregate stability at a depth 0 to 15 cm after 3 yr of sycamore growth on a site adjacent to the present study. A 12-yr-old sycamore plantation had lower soil bulk density and a much increased infiltration rate compared with no-till row crop systems and a 1-yr-old sycamore plantation (Bandaranayake et al., 1996). Although tree roots are likely conducive to soil aggregate formation, an important factor in the improvement of soil hydrologic properties under SRWCs is the formation of a perennial litter layer composed of leaves and fallen tree limbs. A 6.5-yr-old sycamore plantation adjacent to this study exhibited a thick litter layer that included leaves of various stages of decomposition. Although the sycamore crop in the present study did not improve aggregation in the soil fraction prone to erosion (0 to 2.5 cm below the surface), other studies have shown significant reductions in erosion after establishment of woody crops (Mann and Tolbert, 2000; Kort et al., 1998; Thornton et al., 1998; Mitchell, 1997). Most of these reductions occurred after the woody crop had become established on the site, usually two or more years after planting. Erosion is decreased under SRWCs not only by improved soil aggregation and infiltration but also by the litter layer that reduces the impact of raindrops on the soil and slows overland flow. This effect can also be achieved by growing cover crops between tree rows during the establishment of SRWCs (Tolbert et al., 2000).

Two and a half years after a field was converted from a sycamore biomass plantation to a no-till corn system, increases in soil C from the sycamore plantation were still present. The source of this added C appeared to be from tree roots rather than aboveground residues. Soil aggregate stability also was improved by the sycamore plantation, but not at the shallowest sampling depth. The sycamore residues at lower soil depths did not affect plant-available N after fertilization, but some N immobilization may have occurred near the surface. For soils initially low in organic matter, it is possible for a sycamore biomass crop with a rotation length as short as 4 yr to increase soil C concentration and improve soil structure. Longer rotation lengths would likely lead to greater increases in soil C and aggregate stability and perhaps improvements in erosion resistance and infiltration rates. This could, in turn, benefit subsequent row crop production.

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