Pergamon

Biomass and Bioenergy Vol. 15, No. 1, pp. 57–69, 1998

Printed in Great Britain
0961-9534/98 $19.00 + 0.00

PII: S0961-9534(97)10053-8

ENVIRONMENTAL EFFECTS OF GROWING WOODY CROPS ON AGRICULTURAL LAND: FIRST YEAR EFFECTS ON EROSION, AND WATER QUALITY

Frank C. Thornton**, J. Dev Joslin*, Bert R. Bock*, Allan Houston‡,
T. H. Green†, Stephen Schoenholtz‡, David Pettry§ and Don D. Tyler||
*TVA, Atmospheric Sciences, Muscle Shoals, AL 35662, U.S.A.
†Plant and Soil Science, Alabama A and M University, Normal, AL 35762, U.S.A.
‡College of Forestry, Mississippi State University, Starkville, MS 39762, U.S.A.
§Department of Soil Science, Mississippi State University, Starkville, MS 39762, U.S.A.
||West Tennessee Experiment Station, Jackson, TN 38301, U.S.A.

Abstract—The objective of this study is to assess the effects of converting row crop agricultural land to short-rotation-woody-crops (SRWC) on erosion, surface water quantity and quality, and groundwater quality. Three physiographic regions in the Southeast, of varying soils, slope, and erodibility, were used. Replicate plots were equipped with a flume and four pan lysimeters so that event sampling of run-off and groundwater could be conducted. Cropping treatments had little effect on the runoff volumes collected; however, sediment produced by the various treatments was significantly influenced by crop. At all three sites, spring and fall generally had the highest sediment losses. The highest absolute losses of sediment occurred at the Mississippi Delta site. Conventional tilled cotton (*Gossypium hirsutum* L.) lost 16.2 Mg ha^{-1}, compared to 2.3 Mg ha^{-1} for cottonwood (*Populus deltoides* Marsh) over 14 months. While sediment losses at a loess-belt site in west Tennessee were three-fold higher under no-till corn (*Zea maize* L.) than sycamore (*Platinus occidentalis* L), total sediment loss was less than 1 Mg ha^{-1} for both treatments. At the north Alabama site, no-till corn and sweetgum (*Liquidambar styraciflua* L.) with a fescue (*Fescue elitor* L.) cover crop did not differ with respect to erosion. However, sediment losses under sweetgum without a cover crop were significantly higher, exceeding 5 Mg ha^{-1}. Nutrient losses of N and P in both runoff and lysimeters were primarily influenced by spring mineral fertilizer applications. Spring and early summer lysimeter nitrate values exceeded EPA guideline for drinking water in the row crop treatments. © 1998 Published by Elsevier Science Ltd. All rights reserved

Keywords—Short-rotation-woody-crops; erosion; water quality; row crop agriculture.

1. INTRODUCTION

Biomass energy offers possibilities for a sustainable and renewable energy source as we enter the new millennium. The biomass power industry in the U.S. has grown from about 200 MW in 1979 to more than 6000 MW in 1990.[1] The U.S. DOE (Department of Energy) is projecting far greater implementation of biomass power by the year 2010, forecasting that up to 20 GW of capacity will be on line. Present projections assume that one-half of this new generating base will come from dedicated direct-fired plants and the remaining from co-firing and next generation technologies.[2] Whether such projections become a reality is dependent on a range of technological advances and future government energy policy. While biomass energy has the most promise in developing countries[3,4], a number of attributes make biomass power attractive in the U.S., including:

- biomass power would stimulate job creation and rural revitalization
- biomass power offers a secure domestic energy source
- climate change benefits since using biomass is CO_2 neutral and a hedge for utilities against a possible CO_2 tax
- reduction in air pollutant emissions of SO_2, NO_x, and acid rain
- reduced landfill requirements since ash from biomass fueled combustion could be reapplied to land as a plant amendment

The results of an analysis of the potential land base for producing energy crops in the U.S. has shown that the Northeast, South Central and Southeastern states are the most suitable for production of energy crops.[5] In the Southeast, TVA has shown interest in developing biomass power and their analysis

---

**Author to whom correspondence should be addressed.

has shown that short-rotation-woody-crops are capable of accounting for 65–95% of the biomass fuel needed to co-fire in existing fossil plants.[2] Recent TVA biomass resource analyses[6] indicated that bioenergy crop production would primarily be located in the western portion of the TVA service region where the majority of the Valley's agricultural lands are concentrated. Substantial land use changes would be involved and early assessments of both local and regional environmental effects will be required in order to determine the true feasibility of such an undertaking. The magnitude of the land base that could be potentially involved in the production of SRWC, assuming a current yield level of 11 Mg (o.d) ha^{-1}, could range from 255 000 ha for a 5% by weight co-fueling with coal, to a land requirement of nearly 518 000 ha at a 10% fueling rate. Given the land requirements for producing bioenergy crops, it is essential that both local and regional-scale environmental impacts be assessed prior to such an undertaking.

Published predictions of the environmental effects of conversion of cropland to SRWC to date have been almost entirely based upon a combination of what is known about agricultural systems under different types of cultivation and about forest and agricultural systems in general. Very little quantitative information is available and most of this information has come from limited European experience.[7] In general, conversions to SRWC are expected to improve water quality by reducing sediment loss in runoff as well as the movement of pesticides, nitrogen, phosphorous, and other nutrients into surface runoff and groundwater.[8–10] Alterations in runoff and leaching quantities and their timing are also predicted as a result of changes with SRWC rainfall interception, the infiltration of precipitation, and the amount and timing of evapotransporation. Positive effects of conversion on soil physical, chemical, and biological properties have also been predicted.[9,10]

The objective of this paper is to report on the results of the first 14 months of a four-year-study on the conversion of row crop agricultural land to SRWC at three different sites in the Southeastern U.S. At each of these sites, six major categories of environmental effects are being assessed: (1) erosion, (2) surface runoff water quality, (3) groundwater leachate quantity and quality, (4) surface runoff quantity and timing, (5) soil physical properties, and (6) soil biological properties. Soil physical properties being investigated are: (1) aggregate stability, (2) porosity, (3) bulk density, (4) hydraulic conductivity, and (5) penetrometer resistance. Whereas all these types of environmental effects are being studied, the primary emphasis of this preliminary report is on (a) erosion, (b) nutrients in surface runoff, (c) movement of nutrients into the groundwater, and (d) surface runoff quantity. Since only the results from the first 14 months of the study were available at the time of this report, the focus is upon the first year establishment phase and the following second spring. It was generally predicted in a previous description of the research approach taken in this project[10] that few differences would be observed in runoff and groundwater quantity or quality between SRWCs and row crops during the first year "establishment phase." The assumption behind this prediction was that cultural practices, soil exposure, and plant uptake of water and nutrients would be quite similar between SRWCs and traditional agricultural row crops during the first year.

2. MATERIAL AND METHODS

Three sites were selected to represent three physiographic regions within the Tennessee Valley, which were previously identified to contain a significant land base suitable for SRWC production and to be located within a reasonable radius (100 km) of TVA fossil plants that could utilize the feedstock.[6] The three sites chosen for study were: (1) the Delta Research and Extension Center at Stoneville, Mississippi (STNVL), situated in the upper Mississippi Delta, (2) the Ames Plantation (AMES), located in the loess belt of west Tennessee near Grand Junction, and (3) the Alabama A and M University Agricultural Experiment Station (AL A and M) at Hazel Green, located in the Limestone Valley region of northern Alabama. Sites were chosen based on (1) their present and past land use, i.e. sites that had been used for the production of agricultural row crops, (2) their representation of soil series and slope classes appropriate for the production and management of SRWC, and (3) the presence of relatively uniform slopes and soil profiles within a contiguous area that could accommodate at least six 0.25–0.5 ha replicated mini-watersheds.

In order to achieve replication of experimental treatments at each site, small watersheds (about 0.5 ha in size) were created at the three study locations. These artificial watersheds were created by moving soil from outside plot areas to construct berms approximately 0.5 m in height to surround pentagon shaped plots. The longest axis of the pentagon was in the downslope direction on each plot, with a 0.5 m flume, preceded by a 2 m flume approach located at the downslope point of the triangular shaped portion of the pentagon.[10] Each flume was equipped with an ISCO (Lincoln, NE) flow meter and sampler. The flow meters give continuous measurements of flow rates at each flume, and the flow proportional sampler collects water samples during storm events on a flow proportional basis. These samples were used to determine loss of sediment and chemicals in runoff. At STNVL, two treatments were randomly assigned to six plots. At the AMES site, the three SRWC plots, as were the three corn plots, were located contiguously to provide a large block of trees (approximately 5 ha) so that a study of conversion impacts on wildlife could be conducted. Unlike the other two sites, the AL A and M site had four watershed treatments, replicated twice, consisting of: (1) corn (CN), (2) SRWC with no cover crop and complete weed control (TN), (3) SRWC with a cover crop of tall fescue (*Festuca elitor* L.) planted in a 2.4 m strip centered between tree rows (TC), and (4) swithchgrass (*Panicum virgatum* L.) (SG). At all three sites, buffer strips were established between treatments and on the exterior of plots.

SRWC species for a particular site were chosen to be appropriate for the soil and moisture conditions of each site. Eastern cottonwood was planted at STNVL, Sweetgum at AL A and M, and sycamore at AMES (Table 1). Cultural practices used in the production of row crops and tree species were chosen to represent best management practices for practical economic production of crops (Table 1). For the corn crops at AL A and M and Ames Plantation, no-till management was used. The cotton crop at STNVL used conventional tillage. Fescue (*Festuca arundinacea* Schreb.) was planted on the berms at all sites in the fall of 1994 to stabilize them and prevent erosion from berms. At AMES a cover crop of winter wheat (*Triticum aesivum* L.) was established on all plots during late fall of 1994. At AL A and M (except for the TC treatment) and STNVL no cover crop was established, and corn or cotton stubble from the previous year's harvest and cool season weeds provided some soil protection over the winter. The SRWC plots (both TC and TN) at AL A and M and STNVL were subsoiled on the contour prior to tree planting in February and March of 1995. Row crops were planted in April and May of the same year (Table 1). Silvilcultural methods practiced for each SRWC plot included herbicidal control of competing vegetation. Insecticides (Lorsban) were used for cottonwood at STNVL to control stem borers. Normal farming practices for the row crop at each site included standard application of agrichemicals to control weeds and pests.

Table 1. Site characterization of cultural and management practices used in the study

Site	Row crop	
	Crop (planting date)	Tillage
STNVL	Cotton (5-10-95)[a]	Conventional
AL A&M	Corn (4-18-95)	No-till
AMES	Corn (4-10-95)	No-till
	Tree crop	
	Crop (planting date)	Spacing
STNVL	Cottonwood (2-3-95)	1.2 × 3.6 m
AL A&M	Sweetgum (3-6-95)	1.5 × 3.0 m
AMES	Sycamore (2-15-95)	1.5 × 3.0 m

[a] Two applications: 100 kg on April 28, 35 kg on May 30.

Table 2 lists the amount of nutrients applied to the tree and row crops during the 14 months of the study. Whereas cottonwood at the STNVL site, received 58 kg of N in the first year, the trees at the other two sites did not receive N during year one. At the other two sites it was assumed that residual N from the previous year's crop applications would be sufficient to supply N needs for the first year of SRWC growth. Both corn and SRWC plots at the AMES site received an application of dolomitic lime in year one. Row crops in year one and two received N, P, K or lime as needed by recommended soil tests (Table 2). In year two, SRWCs at all three sites received N fertilizer additions, SRWC at AMES and AL A and M also received P in year two (Table 2).

Treatment effects on groundwater quantity and quality were evaluated by collecting leachate from pan lysimeters. In each plot, four pan lysimeters (91 × 61 × 8 cm, L × W × H)

Table 2. Fertilization regimes for each treatment at each sites for the first 15 months of the study

Site	Crop	Nutrient (Amount applied-kg/ha)	
		Year 1	Year 2
STNVL	Cotton	N (135), K (186)	N (135)
	Cottonwood	N (58)	N (58)
AMES	Corn	N (135)[a], P (21), K (25), dolomitic lime (2200)	N (100), P (24), K (102)
	Sycamore	dolomitic lime (2200)	N (135), P (25)
AL A&M	Corn	N (135), P (68)	N (135), P (112)
	Switchgrass	N (68), P (68)	N (68), P (112)
	Sweetgum	None	N (84), P (112)

[a] Two applications: 100 kg on April 28, 35 kg on May 30.

were installed. Of the four lysimeters in each plot, two were placed half-way between tree rows and two were placed between trees within rows. Lysimeters were placed 1.5 m below the soil surface at AMES and AL A and M and 0.8 m below the surface at STNVL. The 1.5 m depth was thought to be a practical limit for the depth of rooting of SRWC crops at the AMES and AL A and M sites. The shallower depth at the STNVL site was chosen to avoid potential problems with groundwater reflux. Lysimeters were installed into the upslope faces of soil pits excavated to a depth of 3.5–4.5 m.

Runoff samples were, with few exceptions, collected within less than 12 h after the end of a precipitation event. Lysimeter samples were normally collected within 24–36 h after precipitation stopped. Both runoff water and lysimeter samples collected at a single location within a single event were composited and refrigerated (4°C) until analysis by a central laboratory. Sediment loss from plots was estimated by EPA method 160.2 by quantitatively weighing the sediment collected within each runoff sample and converting this mass (on an oven dry-basis) to a kg ha^{-1} basis.[11] Colorimetric procedures were used for the analysis of nitrate and ammonium, and ICP analysis was used for the estimation of Ca, Mg, K. Na, B, Fe, Mn, Cu, Zn, Al and bioavailable P.[12] Statistical analysis of data was done using the SAS GLM procedure[13] on an individual site basis. Paired *t*-tests were used to evaluate the difference between SRWC and row crops at the sites consisting of two crops, i.e. AMES and STNVL, and Duncan's New Multiple Range test was used to detect treatment differences among the four treatments at AL A and M. A 0.05 probability level was used to determine statistical significance, unless stated otherwise.

3. RESULTS AND DISCUSSION

3.1. *SRWC establishment*

In general, the conditions for plant establishment and growth of SRWC at the three sites were favorable during the first year of the study. Precipitation amounts for AMES and AL A and M were very close to normal (±5%) for the 10 months following tree planting (April 1995 through January 1996).[14,15] The summer period (June, July, and August) at AMES was wetter than normal, receiving 88 mm of rain above the 30-year average.[15] The STNVL site had a deficit of 162 mm of precipitation in the fall of 1995 (September, October, and November).[16] Survival of planted bare-root seedlings and cottonwood cuttings was excellent, and exceeded 95% at all three sites. Subsequent growth of trees was also very good in the first year with average tree heights in October of 1995 being approximately 5.4 m for cottonwoods at STNVL, 1.3 m for sweetgum at AL A and M, and 1.6 m for sycamore at AMES. Visual observations of tree growth and vigor at the start of the second growing season (spring 1996) confirm the continued survival and health of the trees at all sites. Complete canopy closure was attained with cottonwood at the STNVL site early during the second growing season.

3.2. *Surface water*

3.2.1. *Runoff volume*. Except for the spring seasons at AL A and M, runoff volume was not influenced by treatment at the sites (Fig. 1). While in some instances runoff volumes differed by 50–100%, the variance associated with the runoff parameter was such that statistical significance could not be detected. Among the three sites, C.V.s varied from 52 to 204%, which is similar to those reported by Ruttiman[17] in Switzerland. At AL

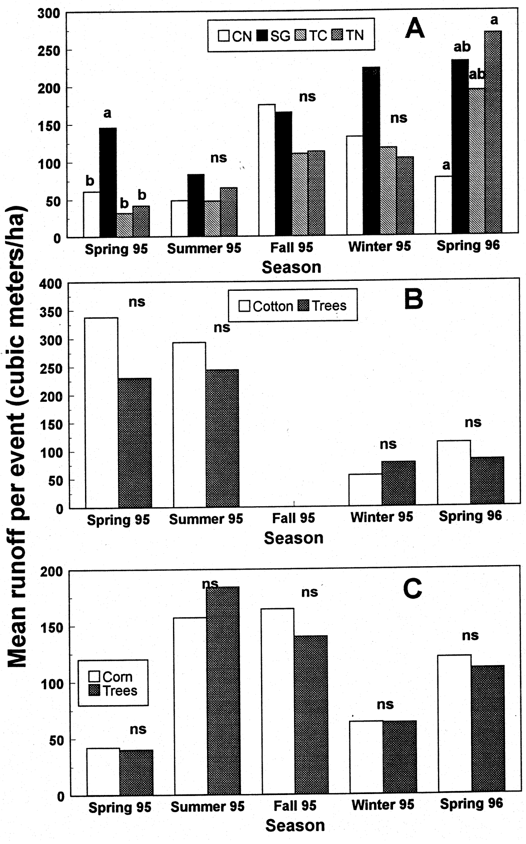

Fig. 1. Mean seasonal runoff volumes for precipitation events within a given season for (A) AL A and M, (B) STNVL, and (C) AMES. Bars with a different letter for a given season at AL A and M are significantly different; for the other two sites the probability level for the *t*-test is given.

A and M, the SG treatment had a statistically greater runoff amount in the spring of 1995 and also exhibited a trend of higher runoff amount in the other seasons (Fig. 1). Among the sites, AL A and M also had the highest ratio of runoff to total rainfall with an overall ratio among treatments of 0.48, meaning that 48% of the precipitation falling on the soil was runoff. For the AMES site and the STNVL, site the overall ratio of runoff to rainfall was 0.29 and 0.32, respectively. The higher runoff fraction at AL A and M is reflective perhaps of both the greater slopes at this site, lesser ground cover, a higher amount of rock fragments on the soil surface, and a higher soil clay content. Field research in Greece has demonstrated a 2–3-fold increase in runoff from replicated experimental plots as the surface cover of the plots increased from 0 to 17.8% rock fragments.[18]

3.2.2. *Sediment*. At each of the three sites, there were statistical treatment differences in mean sediment loss per event (Fig. 2), and large differences were observed in the total seasonal sediment losses at some sites (Fig. 3). Except for AL A and M, spring and fall have been the seasons of greatest sediment loss. The AMES site had the lowest absolute amount of sediment of the three sites with a total of 0.31 Mg ha^{-1} sediment loss per hectare for trees and 0.84 Mg ha^{-1} for corn. While this difference between treatments at AMES is nearly 3-fold, these sediment loss rates are extremely small, especially for this highly erodible loess soil. Risse[19] reported that annual soil losses averaged 3.51 Mg ha^{-1}, for more than 1700 plot-years of data from a wide variety of sites (208) in North America. While the proportion of precipitation resulting in runoff at the AMES and STNVL site were similar (data nor reported), there was greater soil removal at the STNVL site (Fig. 3). This result is not unexpected since the cotton at the STNVL site was conventionally tilled, whereas corn at the AMES site was no-till with a winter wheat crop established in the fall of 1994 and 1995. It should also be noted that at AMES the sycamore trees were planted into a cover crop of wheat that was "burned down" with glyphosphate in late spring 1995, so that there was far less potential for offsite movement of soil than at STNVL, which only had bare soil after tree planting.

The STNVL site had the greatest total loss of sediment of any site (Fig. 3), with losses under cotton (16.1 Mg ha^{-1}) greatly exceeding losses under cotton (2.3 Mg ha^{-1}). Over 80% of the sediment loss in cotton occurred in a single 57 mm rainfall on 24 March 1996, where almost 13 Mg ha^{-1} were lost. The data exhibited the typical pattern in which a few, four to six, runoff events predominant in terms of their contribution to total runoff volume.[20] For this particular event we believe that the large sediment loss was related to soil crusting that decreased infiltration and increased runoff. Cultivated silty and loamy soils are most prone to crusting which is the result of disaggregation of soil particle, displacement of soil particles, and the reorganization of soil materials into denser more continuous structural units that lower infiltration rates.[21,22] The events leading up to the large sediment loss for cotton, 13 Mg ha^{-1}, on 24 March 1996, support this contention. Firstly,

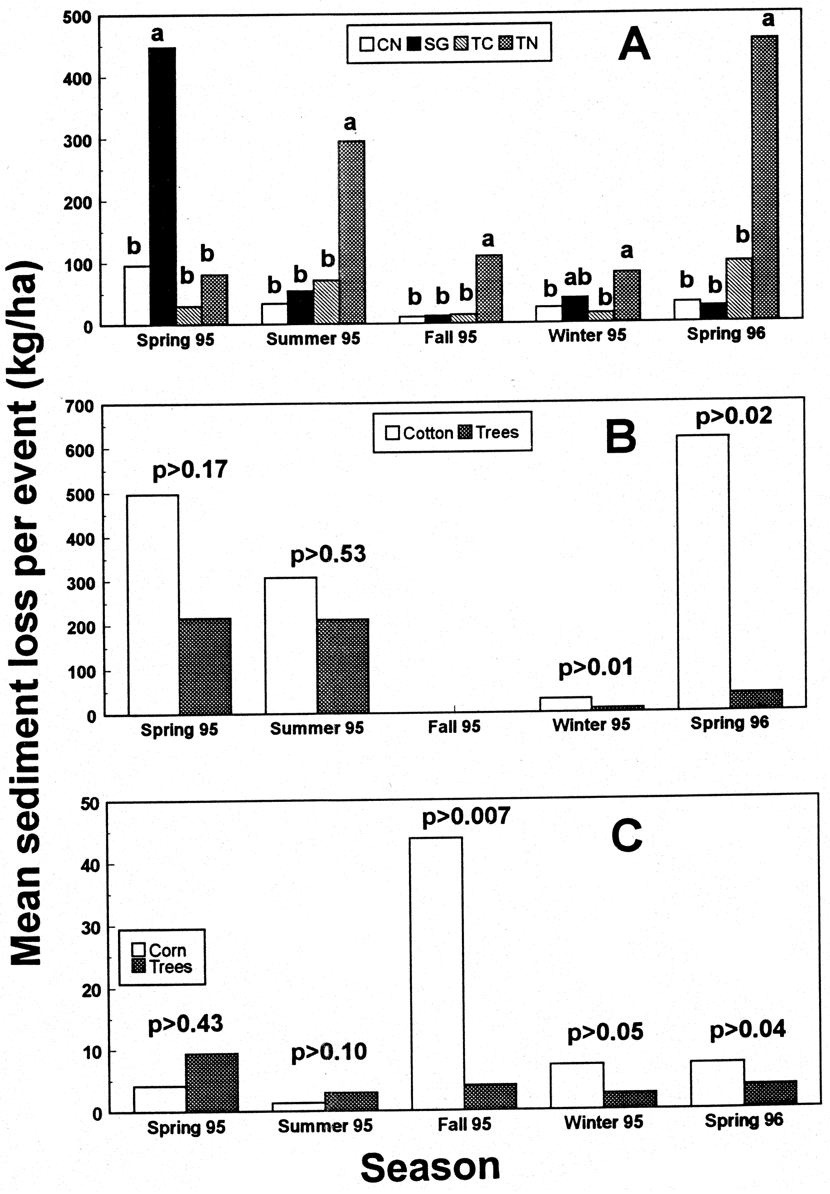

Fig. 2. Mean seasonal sediment loss averaged for precipitation events within a given season for (A) AL A and M, (B) STNVL, and (C) AMES. Bars with a different letter for a given season at AL A and M are significantly different at the $P = 0.05$ level; for the other two sites the probability level for the *t*-test is given.

the soil had been previously ploughed, thereby lowering soil aggregation. Secondly several preceding smaller rain events apparently contributed to soil crusting. SRWC plots, in contrast, received some soil surface protection from past tree litter and weeds, while sediment runoff was probably reduced by the positioning of tree rows perpendicular to the slope. The pattern of erosion at the STNVL site during later rain events in the spring 1996 also probably reflect the influence of a developed tree canopy. By late spring 1996, the cottonwoods had nearly complete canopy cover of the 3.6 m space between rows, resulting in appreciable canopy interception of rain and decreasing the potential for erosion compared to the cotton crop.

At the AL A and M site, the SG and TN treatments lost the most sediment over the 14 month period, 5.1 and 6.0 Mg ha^{-1}, respectively (Figs 2 and 3). A major portion of the loss in the SG treatment occurred in spring

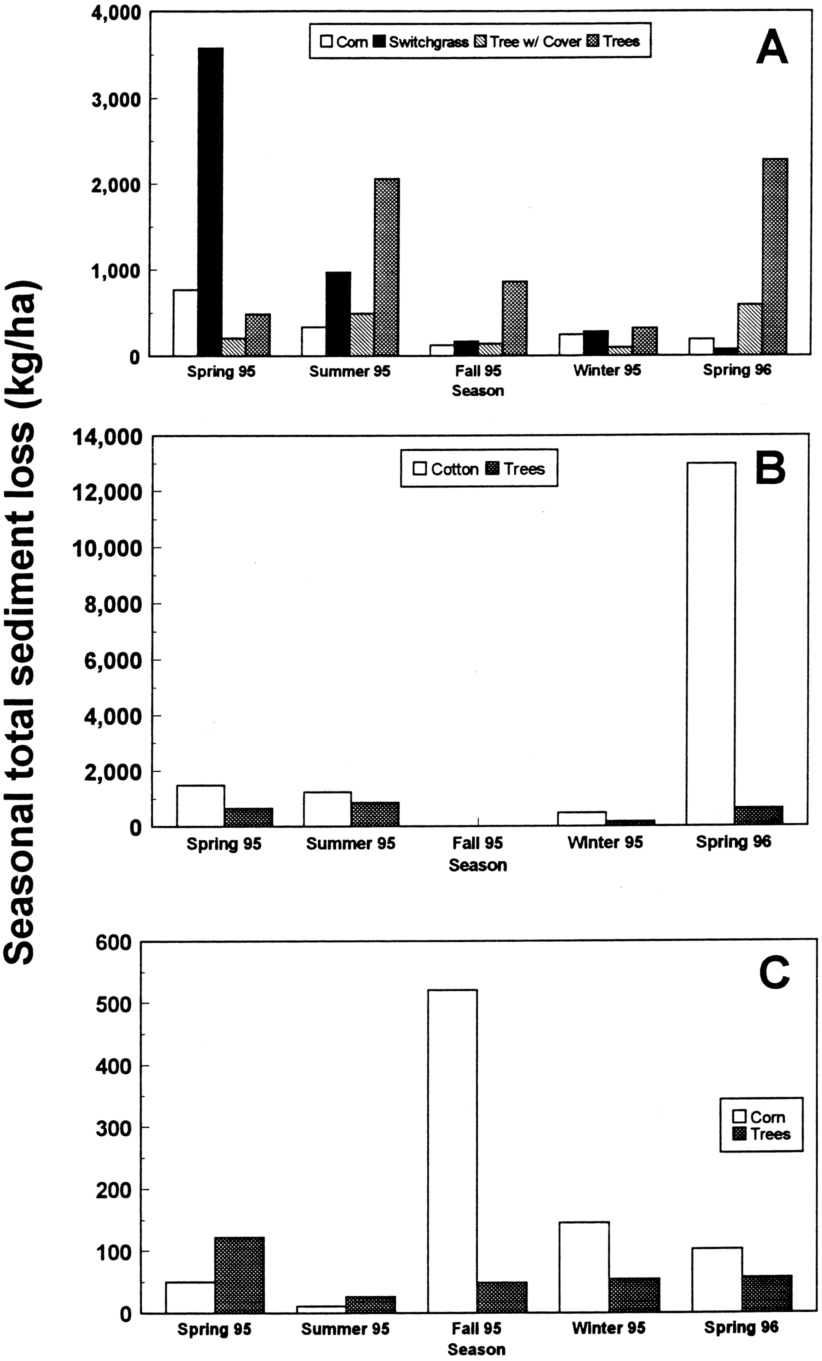

Fig. 3. Total seasonal sediment loss for (A) AL A and M, (B) STNVL, and (C) AMES.

and summer when switch grass was being established and there was little ground cover. Once switchgrass became well established by the spring of 1996, sediment loss from SG plots was significantly reduced compared to the previous spring and summer erosion amounts in SG. The CN and TC treatments behaved similarly in terms of mean sediment loss on a seasonal basis (Fig. 3). TN had significantly greater mean sediment loss when compared to either the CN or TC treatment (Fig. 2), but this result should be expected since the TN plots had almost no plant residue on the soil surface, whereas the CN plot had corn residue from the previous years harvest and the TC plot had a 2.4 m strip of fescue

Table 3. Seasonal means of nutrient losses per runoff event measured at the three study sites

	AL A & M											
Season	NO_3-N (kg ha^{-1})				NH_4-N (kg ha^{-1})				Bio P (kg ha^{-1})			
Spring 95[†]	CN[‡]	SG	TC	TN	CN	SG	TC	TN	CN	SG	TC	TN
	0.50^{b}*	1.6^{a}	0.08^{b}	0.003^{b}	0.16^{b}	0.57^{a}	0.01^{b}	0.003	0.08^{b}	0.24^{a}	0.02^{b}	0.01^{b}
		F = 6.38 (0.002)**				F = 5.93 (0.003)				F = 7.12 (0.001)		
Summer 95	0.03^{a}	0.30^{a}	0.04^{a}	0.10^{a}	0.02^{a}	0.12^{a}	0.01^{a}	0.03^{a}	0.03^{a}	0.06^{a}	0.04	0.04^{a}
		F = 2.27 (0.09)				F = 1.52 (0.22)				F = 0.64 (0.59)		
Fall 95	0.02^{a}	0.06^{a}	0.02^{a}	0.07^{a}	0.03^{a}	0.05^{a}	0.05^{a}	0.06^{a}	0.09^{a}	0.07^{ab}	0.04^{ab}	0.01^{b}
		F = 1.43 (0.25)				F = 0.45 (0.71)				F = 2.04 (0.12)		
Winter 95	0.01^{a}	0.02^{a}	0.01^{a}	0.004^{a}	0.03^{a}	0.04^{a}	0.04^{a}	0.01^{a}	0.07^{a}	0.07^{a}	0.03^{ab}	0.0^{b}
		F = 0.32 (0.81)				F = 0.68 (0.57)				F = 2.29 (0.10)		
Spring 96	0.13^{a}	0.07^{a}	0.12^{a}	0.10^{a}	0.14^{a}	0.07^{a}	0.18^{a}	0.15^{a}	0.02^{a}	0.02^{a}	0.02^{a}	0.05^{a}
		F = 0.07 (0.97)				F = 0.14 (0.93)				F = 1.09 (0.38)		

	STNVL					
	NO_3-N (kg ha^{-1})		NH_4-N (kg ha^{-1})		Bio P (kg ha^{-1})	
	Cotton	Tree	Cotton	Tree	Cotton	Tree
Spring 95[†]	0.31	0.24	0.006	0.22	0.11	0.04
	F = 0.48 (0.52)		F = 5.36 (0.08)		F = 12.35 (0.02)	
Summer 95	0.001	0.02	0.0	0.06	0.001	0.04
	F = 1.07 (0.33)		F = 3.24 (0.12)		F = 0.95 (0.36)	
Fall 95	No Samples		No Samples		No Samples	
Winter 95	0.002	0.005	0.0007	0.0002	0.02	0.02
	F = 1.23 (0.27)		F = 0.91 (0.34)		F = 0.06 (0.80)	
Spring 96	0.04	0.02	0.004	0.006	0.09	0.02
	F = 3.19 (0.08)		F = 0.55 (0.46)		F = 5.04 (0.03)	

	AMES					
	NO_3-N		NH_4-N		Bio P	
	Corn	Trees	Corn	Trees	Corn	Tree
Spring 95	0.63	0.002	0.11	0.01	0.05	0.01
	F = 15.39 (0.0007)		F = 11.93 (0.002)		F = 7.29 (0.01)	
Summer 95	0.01	0.005	0.01	0.01	0.07	0.16
	F = 1.16 (0.29)		F = 0.07 (0.79)		F = 1.57 (0.22)	
Fall 95	0.14	0.04	0.01	0.02	0.09	0.18
	F = 6.8 (0.01)		F = 2.24 (0.14)		F = 5.33 (0.030)	
Winter 95	0.01	0.01	0.005	0.007	0.01	0.02
	F = 3.15 (0.08)		F = 1.47 (0.23)		F = 2.83 (0.10)	
Spring 96	0.09	0.15	0.03	0.65	0.04	0.40
	F = 0.86 (0.36)		F = 5.06 (0.03)		F = 5.93 (0.02)	

[†]Seasons are designated as: spring = March, April, May; summer = June, July, August; fall = September, October, November; winter = December, January, February. Spring 1995 data did not include March.[‡]CN, corn; SG, switchgrass; TC, sweetgum trees with cover crop; TN, trees with no cover crop.*Means within a season with different letters are significantly different at the $P = 0.05$ level by Duncan's New Multiple Range Test.**F statistic and probability level associated with ANOVA for a given parameter.

that helped abate sediment loss on plots. The inclusion of a cover crop (TC) resulted in a fourfold decrease in sediment loss over the 14 month period or 1.5 Mg of sediment per hectare.

3.2.3. *Nutrients*. Table 3 presents the seasonal means for three key water quality parameters associated with runoff. Differences among treatments were primarily associated with spring (both spring 1995 and spring

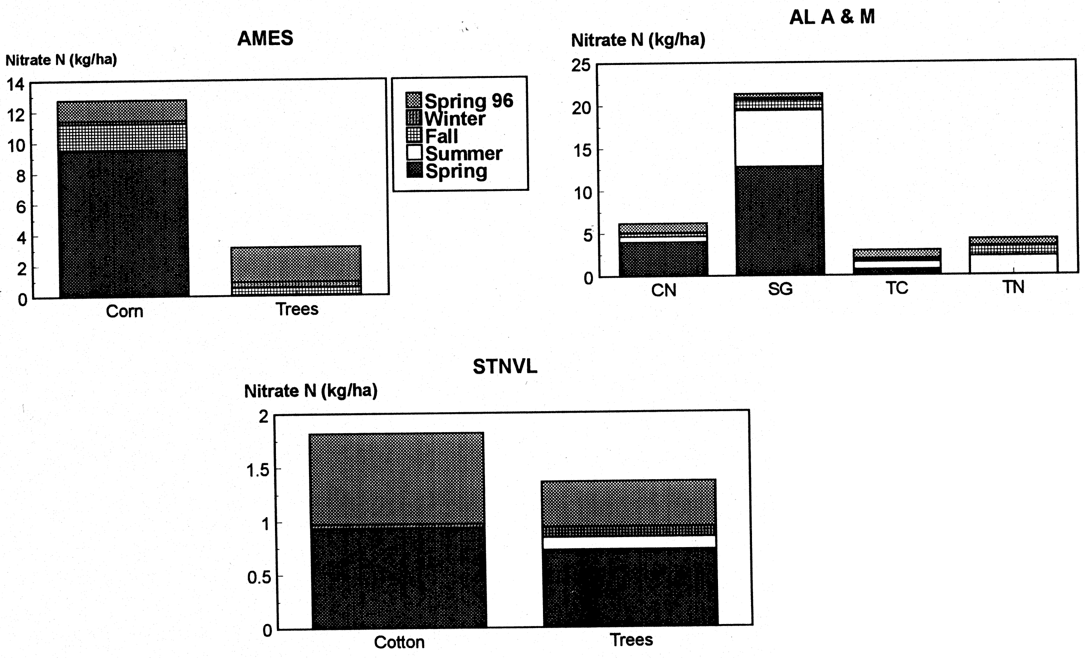

Fig. 4. Nitrate-N loss in runoff by seasonal for the three study sites.

1996) when fertilizer applications were made. In 11 out of 18 possible comparisons for mass loss of NO_3^--N, NH_4^+-N, and bioavailable P, (mass loss for each nutrient is calculated as runoff concentration times volume of runoff for each discrete precipitation event) there was significantly greater export of nutrients from crop plots (corn, cotton, and switchgrass) than SRWC plots (Table 3 and Figs 4–6). Exceptions to this include NH_4^+ at STNVL and AMES, bioavailable P at AMES where mass losses under trees exceeded that under crops. The largest losses of nutrients applied occurred in runoff at the AL A and M site, where 25% of the applied N (12.8 kg NO_3^--N and 4.6 kg NH_4^+-N ha^{-1}) was lost in the switchgrass treatment in the spring of 1995. Even with double the N application rate of

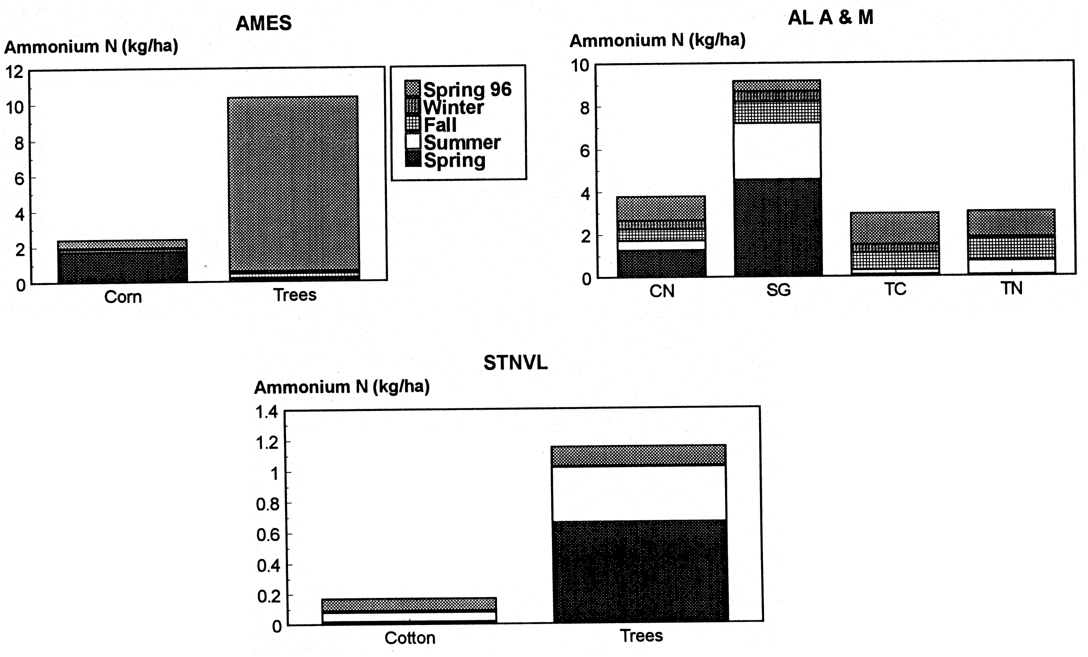

Fig. 5. Ammonium-N loss in runoff by seasonal for the three study sites.

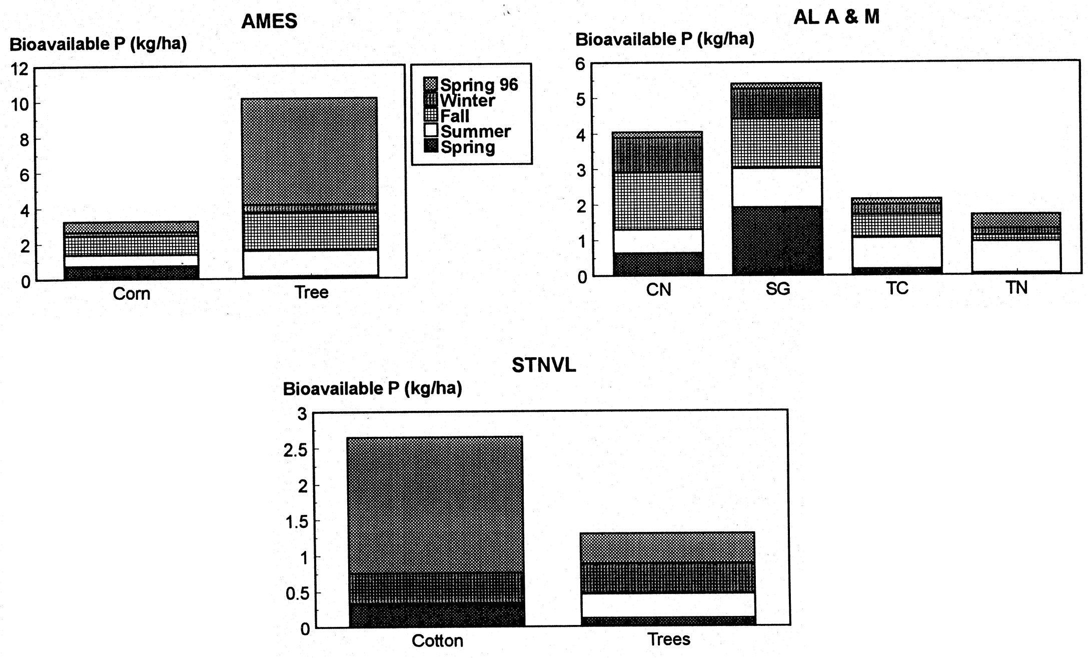

Fig. 6. Bioavailable P loss in runoff by seasonal for the three study sites.

168 kg N ha^{-1}, CN at AL A and M lost less than 2% of the applied N in the two spring applications. The higher loss rate of N for switchgrass in spring 1995 is related to the slow establishment of the switchgrass after planting. Once switchgrass was established, the same 68 kg ha^{-1} application in spring 1996 resulted in a loss of about 1 kg of NO_3^- and NH_4^+ after the spring 1996 application (Figs 4 and 5).

Large pulses of NO_3^- in runoff water were also detected in the corn plots at AMES for spring 1995 (Fig. 4, Table 3). In contrast, fertilizer application to trees at AMES at the start of year two (spring 1996) resulted in significant NH_4^+ loss compared to corn with tree plots losing more than 3-fold that of corn (Table 3, Fig. 5) However, our data revealed that a large portion of the NH_4^+ loss for trees occurred at the end of March 1996, prior to fertilizer application. We recorded the highest NH_4^+ concentrations, up to 2.77 mg l^{-1}, in the AMES SRWC plots prior to the spring 1996 fertilization. We speculate that N mineralization within SRWC plots was in excess of microbial or plant demand early in the season and that this NH_4^+ was subject to loss in surface runoff. The spring 1996 fertilizer application at AMES also resulted in significantly greater bioavailable P loss from SRWC plots, which also lost about 3-fold that of corn (Fig. 6). During the fall and winter, P loss from the tree treatment at AMES was also greater than that from corn (Table 3).

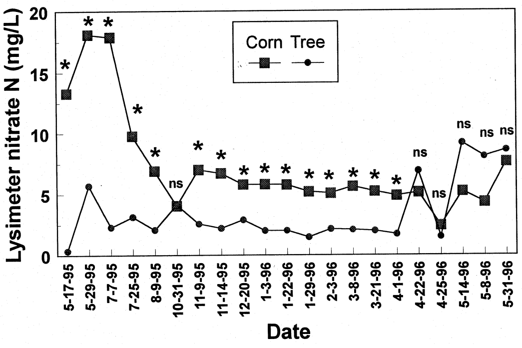

Fig. 7. Lysimeter NO_3^- concentrations for corn and sycamore at the AMES site. A * indicates a significant *t*-test for a given date, ns is not significant.

In contrast to AMES, the bioavailable P losses in runoff at AL A and M were lowest in the SRWC plots (Fig. 6). We attribute the higher runoff of bioavailable P under SRWC at AMES to greater release of organically bound P from the SRWC plots, due in part to (1) uptake by the 1995 fall wheat cover crop on the corn plots, and (2) mineralization of a larger pool of dead weed and old cover crop residues[23] and (3) differences in uptake patterns by the primary crops. Estimates of the range of P flux related to organic P mineralization[23] range from 6 to 23 kg ha^{-1} y^{-1}. In contrast to AMES and AL A and M, the loss of nutrients in runoff at STNVL was minimal

(Figs 4–6). In only one instance did loss exceed more than 2 kg ha^{-1} for a single season (Table 3, Figs 4–6). For the establishment period at all three sites, measured differences in N and P runoff for the various treatments across the three sites was primarily related to the timing of mineral fertilizer application, the timing of precipitation events, the rapid cycling of N and P in weed and cover crop residues, and differences in uptake patterns of the primary crop. We anticipate that as a forest floor develops in the tree systems that the role of microbial N and P will become more important in controlling the nutrient dynamics of these systems and the attendant export via surface water. We also anticipate that the extensive root systems now established in SRWCs will minimize nutrient losses in runoff and groundwater in the remainder of the study.

3.3. *Groundwater*

During the 14 month period a total of 50 precipitation event collections of lysimeter water samples were made at the three sites. Twenty-two collections were made at the AL A and M site, 17 collections at AMES, and 11 collections at STNVL. Lysimeter nitrate concentrations for the AMES and AL A and M site are presented in Figs 7 and 8. A very clear and consistent trend in lysimeter NO_3^- was evident for the AMES site throughout the first year and up until fertilizer was applied to both the trees and corn in the second year (Fig. 7). Throughout the first ten months, corn consistently had significantly higher nitrate levels than trees except for the 31 October 1995 date. After fertilization the second year, the tree plots had higher nitrate levels, although there was no statistically significant difference between the treatments. It is worth noting that after the spring 1995 fertilizer application, lysimeter samples exceeded the EPA limit[24] of 10 mg N l^{-1} in the corn treatment at AMES, but following the spring 1996 application, the highest value was 8 mg l^{-1}.

In the spring of 1995, we measured a similar pulse of nitrate in the lysimeter samples in the corn at AL A and M (Fig. 8); however, due to the small number of replicate samples, these differences were not statistically different. Following the higher nitrate values in the corn treatment in the spring of 1995, the tree plots (TC and TN) had the highest nitrate lysimeter concentrations from October, 1995 through April 1996. Conversely, after the high spring SG nitrate lysimeter values, the SG treatment had the lowest nitrate lysimeter values throughout most of the October to April period (Fig. 8). Part of the reason for this reversal was probably the high loss of applied nitrate in runoff from SG plots (25% was of spring 1995 applied N was lost as either NO_3^- or NH_4^+). While neither tree treatments (TC and TN) received N in the first year, lysimeter nitrate samples from these plots were typically about 2-fold that of switchgrass which received 68 kg N ha^{-1} in both year one and two (Table 2). The lower nitrate values in the second year are likely the result of significant N uptake by switchgrass that had become well established by the spring of 1996. We hypoth-

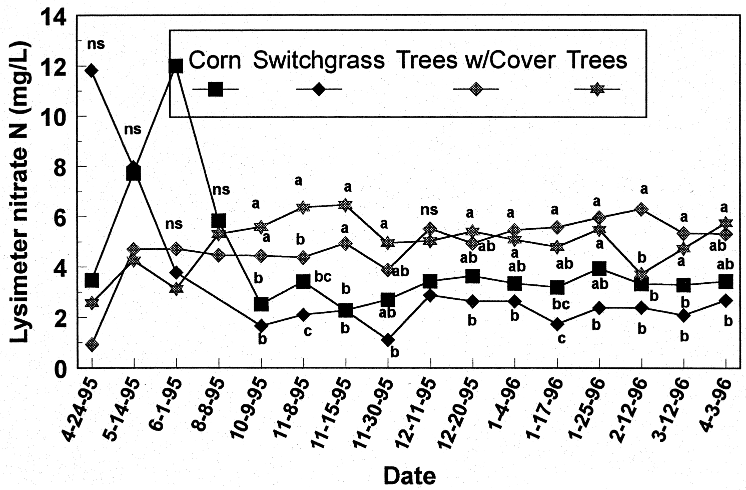

Fig. 8. Lysimeter NO_3^- concentrations for treatments at AL A and M. Treatment means for a given date with different letters are significantly different.

esize that the higher nitrate values in the tree treatments at AL A and M, irrespective of the N additions, is due to greater mineralization in the tree treatments related to the disturbance effect of planting sweetgum seedlings within the subsoiled slits created in the tree plots. Rates of mineralization, and nitrification, generally increase after disturbance.[25] This disturbance effect typically lasts several years and then mineralization rates and soil N pools return to those before disturbance. This observation is supported by the fact that for the tree plots during the first year of the study (April 1995 until mid-April 1996 when N was added to the tree treatments) the flux of nitrate-N collected in lysimeters (data not shown) was 2-fold that of either corn or switchgrass, despite the fact that fertilizer N was added to both treatments. The cumulative NO_3^--N flux values for the first 12 months for the CN, SG, TC, and TN plots were 15.1, 14.1, 28.6 and 34.9 kg NO_3^--N ha^{-1}, respectively. Further, inspection of NO_3^--N flux data for lysimeters results (data not shown) reveal that in all but two instances there is no significant difference among the treatments in the volume of leachate water collected. This result implies that NO_3^- concentrations, not leachate volumes, are responsible for these differences in NO_3^--N flux.

Very limited lysimeter water samples were available from the STNVL site. Just as the below normal rainfall for the fall 1995 period produced no runoff samples (Table 3), no lysimeter samples were collected for this season either. Of the 11 events with samples collected at SNVL, only eight had complementary samples from both the cotton and tree plots. Due to the paucity of samples at STNVL these data are not presented; however, nitrate concentrations were low in both tree and cotton treatments ranging from 0.38 to 3.53 mg l^{-1}, based on individual event averages. Analysis of other nutrient elements in the lysimeter samples (NH_4^+, P, Ca, Mg, K) did not show any treatment differences at the three sites and are therefore not presented.

4. CONCLUSIONS

The data presented support the hypothesis that conversion of existing cropland to SRWC will improve surface runoff and groundwater quality. Even during the first year of the study, when trees were just becoming established, measurable differences between trees and row crops were recorded in water quality. It is expected that these differences will become more pronounced with time. For example, STNVL, with the most rapidly growing SRWC species, cottonwood, demonstrated that sediment loss in runoff in the first 14 months could be reduced 85% compared to cotton. AMES as well, showed significantly higher losses of sediment under corn in four out of the five seasons examined. At the AL A and M site SG had the highest sediment losses during the initial establishment phase, but once established, sediment losses were low. Data from AL A and M indicated that a cover crop of fescue could effectively control erosion but that without soil surface protection, i.e residue from no-till corn, erosion could be higher under trees during the establishment phase. Nutrient losses of N and P in runoff were primarily linked to the applications of mineral fertilizers in the spring and were generally, but not always, higher under crops. Nitrate values in lysimeter samples showed that there were instances where NO_3^- exceeded EPA standards in row crops, but were consistently well below the 10 mg N l^{-1} limit[24] for the SRWC treatments.

REFERENCES

1. R. L. Bain, Electricity from biomass in the United States: status and future direction. *Bioresource Tech.* **46,** 86–93 (1993).
2. C. E. Noon and M. J. Daly, GIS based biomass resource assessment with BRAVO. *Biomass and Bioenergy* **10,** 101–109 (1996).
3. C. R. McGowin, Biomass for electric power in the 21st century. *Biomass and Bioenergy* **10,** 69–70 (1996).
4. J. L. Easterly and M. Burnham, Overview of biomass and waste fuel resources for power production. *Biomass and Bioenergy,* **10,** 79–92 (1996).
5. L. L. Wright and E. E. Hughes, U.S. carbon offset potential using biomass energy systems. *WASP* **70,** 483–497 (1993).
6. M. Downing and R. L. Graham, Evaluating a biomass resource: the TVA region wide biomass resource assessment model. In *Proceedings of First Biomass Conference of the Americas: Energy, Environment, Agriculture, and Industry.* Burlington, VT, 30 August–2 September, 1993.
7. Wood Supply Research Group, University of Aberdeen, Short rotation forestry handbook. Department of Forestry, Aberdeen, Scotland. Internet address, http://www.abdn.ac.uk/wsrg/index.htm, 1996.
8. Office of Technology and Assessment (OTA, US Congress), Potential environmental impacts of bioenergy production—background paper, OTA-BP-E118. U.S. Govt Printing Office, Washington, DC, 1993.
9. J. W. Ranney and L. K. Mann, Environmental considerations in energy crop production. *Biomass Bioenergy* **6,** 211–228 (1994).

10. J. Joslin and S. H. Schoenholtz, Measuring the environmental effects of converting cropland to short-rotation-woody-crops: a research approach. *Biomass and Bioenergy*, **13,** 301–311 (1997).
11. U.S. Environmental Protection Agency, Methods for chemical analysis of water and wastes, Revision, 1983. 160.2 - Residues, nonfilterables (Gravemetric, dried at 105°C. EPA/600/4 79-020, Cincinnati, OH, 1983.
12. A. N. Sharpley, W. W. Troeger and S. J. Smith, The measurement of bioavailable phosphorus in agricultural runoff. *J. Environ. Qual.* **20,** 235–238 (1991).
13. SAS Institute, Companion for the Microsoft Windows environment. Version 6 edn. SAS, Cary, NC, 1993.
14. National Oceanic and Atmospheric Administration, *Climatological Data. Alabama*. Vol. 100 (1–12). U. S. Department of Commerce, Natl. Climate Data Center Asheville, NC, 1995.
15. National Oceanic and Atmospheric Administration, *Climatological Data. Tennessee*, Vol. 100 (1–12). U.S. Department of Commerce, Natl Climate Data Center, Asheville, NC, 1995.
16. National Oceanic and Atmospheric Administration, *Climatological Data. Mississippi*, Vol. 100 (1–12). U.S. Department of Commerce, Natl Climate Data Center Asheville, NC, 1995.
17. M. Ruttiman, D. Schaub, V. Prasuhn and W. Ruegg, Measurement of runoff and soil erosion on regularly cultivated fields in Switzerland—some critical considerations. *Catena* **25,** 127–139 (1995).
18. N. C. Moustakas, C. S. Kosmas, N. G. Danalatos, N. Yassoglou and I. Rock fragments, Their effects on runoff, erosion and soil properties under field conditions. *Soil Use Management* **11,** 115–120 (1995).
19. L. M. Risse, M. A. Nearing, A. D. Nicks and J. M. Laflen, Error assessment in the universal soil loss equation. *Soil Sci. Soc. Am. J.*, **75**, 825–833 (1993).
20. W. Viessman, Jr, T. E. Harbaugh and J. W. Knapp, *Introduction to Hydrology*. Intext, New York, 1972.
21. Y. Le Bissonnais, M. J. Singer and J. M. Bradford, Assessment of soil erodibility: the relationship between soil properties, erosion processes and suseptibility to erosion. In *Farm Land Erosion: in Temperate Plains and Hills*, ed. S. Wicherrek. Elsevier Science, Amsterdam, 1993, pp. 87–96.
22. Y. Le Bissonnais, B. Renaux and H. Delouche, Interactions between soil properties and moisture content in crust formation, runoff and interrill erosion from tilled loess soils. *Catena* **25,** 33–46 (1995).
23. A. N. Sharpley, Soil phosphorus dynamics: agronomic and environmental impacts. *Ecol. Engineering* **5,** 261–279 (1995).
24. U.S. Environmental Protection Agency, *Quality criteria for water*. GPO, Washington, D.C., 1976.
25. P. M. Attiwill and M. A. Adams, Tansley review no. 50: nutrient cycling in forests. *New Phytol.* **124,** 561–582 (1993).