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Soil and water quality implications of production of herbaceous and woody energy crops

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Abstract

Field-scale studies in three physiographic regions of the Tennessee Valley in the Southeastern U.S. are being used to address the environmental effects of producing biomass energy crops on former agricultural lands. Comparison of erosion, surface water quality and quantity, and subsurface movement of water and nutrients from woody crops, switchgrass and agricultural crops began with crop establishment in 1994. Nutrient cycling, soil physical changes, and productivity of the different crops are also being monitored at the three sites. During the first year of establishment, maximum sediment losses from all crops occurred in the spring and fall when the soils were exposed and rainfall intensities were greatest. In Alabama, sediment losses were greater from switchgrass and sweetgum planted without a cover crop than from sweetgum with a cover crop. Nutrient losses in runoff and subsurface water were greatest after spring fertilizer application. These field studies are providing data on how effects of biomass crop production change with crop maturity and site ground cover compared with production of annual row crops. Data from these sites are being used in conjunction with a watershed-scale study established in 1997 to identify management techniques to maximize sustainability of biomass crop production. These and related studies will be used to develop and model nutrient and hydrologic budgets for biomass crop plantings to identify potential constraints to sustainable deployment of biomass crops.

Introduction

A combination of concern over the increase in atmospheric CO_2 and the need for greater dependence on domestic energy sources has prompted interest in alternative energy sources derived from biomass. Use of short-rotation energy crops to produce as much as four percent of the current domestic energy requirement by 2010 (Hohenstein and

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Wright 1994) could require as much as 1 million dry tons of biomass per year (Ranney et al. 1987). At a yield of 4 dry tons per acre per year (Graham and Downing 1995), this could require as many as 250,000 acres of land to provide this feedstock. This land base for bioenergy crops will most likely be from conversion of agricultural land or land formerly placed in agricultural set-aside programs because of their erosiveness.

For this land use conversion to be acceptable to producers, the public, decision-makers, and environmental groups, the environmental impacts of biomass crop production compared with traditional row crop production must be quantified. Pimental and Krummel (1987), Hohenstein and Wright (1994), and Ranney and Mann (1994) have predicted that conversion of agricultural lands to short-rotation woody crops will result in reductions in soil erosion and chemical losses in runoff and groundwater. Benefits in terms of carbon sequestration and reduced greenhouse gases have been projected from producing biomass crops and replacing fossil fuel use with these crops (Hall et al. 1990, Wright et al. 1992, Hohenstein and Wright 1994). Quantifiable field data are needed to demonstrate these benefits for regions of the U.S. with the greatest identified potential for biomass crop production.

Pimental and Krummel (1987) estimated that the average erosion rate for croplands in the U.S. is 18 Mg per ha per year compared with a rate of 0.2 Mg per ha per year for forage, hay crops, and natural forests. By comparison, the erosion estimates for short-rotation woody crops (SRWC) range from 2-17 Mg per ha per year - most of which is estimated to occur in the first stages of the rotation and to decline after establishment to 2-4 Mg per ha per year (Pimental and Krummel 1987). Ranney and Mann (1994) estimated that higher erosion would occur during the first two years of establishment and would be lower overall than for agricultural crops. Higher erosion with SRWC than forests, however, is anticipated because of the more frequent harvesting and reduced ground cover. Quantitative comparisons of erosion rates from biomass crops and agricultural crops over a crop rotation are not available.

Comparisons of carbon sequestration show that biomass crops sequester more carbon than agricultural crops but less than forests. Gebhart et al. (1994) found that Conservation Reserve Program (CRP) set-aside lands sequestered more carbon than agricultural land but less than pasture land. Cultivated croplands are estimated to lose 2.7 million metric tons of carbon per year in addition to the 35.4 million metric tons from fossil fuel use and pesticide manufacture. In Minnesota, Hansen (1993) found that hybrid poplar plantings increased soil carbon storage at an average rate of 1.6 Mg per ha per year. Grigal and Berguson (1997) suggest that SRWC can increase soil carbon storage by 10-20 Mg per ha over a 10-15 year rotation. Results to date from biomass crops show a decline in soil carbon with SRWC establishment, but within five years of establishment they begin to reach the higher accretion levels.

Only limited information is available to quantify the potential environmental benefits of biomass crop production for soil and water quality and carbon sequestration compared with annual row crops (Green et al. 1996, Thornton et al. 1996, Tolbert et al.

1997). If SRWC and herbaceous crops are to be grown as biomass energy sources while providing environmental benefits, data must be available for critical examination of the effect of production of these crops on erosion, water quality, chemical and fertilizer requirements and use, and biodiversity (Ranney and Mann 1994). This paper describes a 3-site study in the southeastern U.S. that is quantifying the benefits and potential impacts of biomass crop development for soil and water quality. This study is designed to identify and incorporate management methods for production of woody and herbaceous crops that can minimize off-site effects and provide environmental enhancement.

Materials and Methods

Three locations representing three physiographic regions within the Tennessee Valley identified as having the potential for biomass crop production (Downing and Graham 1996) were selected as research sites. At each site six major categories of environmental effects -- (1) erosion, (2) surface runoff water quality, (3) groundwater leachate quantity and quality, (4) surface runoff quantity and timing, (5) soil physical and chemical properties, and (6) soil biological properties -- are being assessed for biomass crops compared with agricultural row crops. The study is funded jointly by the U.S. Department of Energy (DOE), the Tennessee Valley Authority, and the Southeastern Regional Biomass Program, with cost-sharing by Alabama A&M University, Mississippi State University, and The University of Tennessee.

Replicate large-scale research plots ranging from 0.2 to 2.5 ha each are located at each of the agricultural research stations owned by the individual universities. For each of the sites, crops and SRWC comparisons that would be typical of the individual regions were chosen. At the Alabama site two replicates each of sweetgum (*Liquidambar styraciflua* L.) were planted on 1.5 by 3 m spacing on 0.2 and 0.5 ha plots established (1) with a 2.4 m cover crop of fescue (*Festuca elatior* L.) planted down the center of the rows and (2) on plots established without a cover crop (Green et al. 1996, Malik et al. 1996). Replicated plots of switchgrass (*Panicum virgatum*) and no-till corn (*Zea mays* L.) for grain production were also established at the same scale at the Alabama site. The Alabama site is typical of the ridge and valley province of the Tennessee Valley with a soil classified as a Decatur and Cumberland silt loam, undulating phases, with 2 to 6% slope with good natural drainage (Green et al. 1996).

At the Mississippi site, cotton (*Gossypium hirsutum* L.) and eastern cottonwood (*Populus deltoides* Bartr.) were established on agricultural land dominated by a Bostket silt loam soil, which is a fine loamy, mixed, thermic Mollic Hapludalfs. This alluvial soil is considered highly productive for agriculture and has a slope of 0.2% (Mitchell 1997). Cotton was established using conventional cultivation methods; and cottonwood cuttings were established at a spacing of 1.2 m within each row by 3.6 m between each row with each of the 2.5 ha experimental plots.

At the Tennessee experimental station, sycamore (*Platanus occidentalis*) and corn, as a silage crop, were established on a Memphis-Loring silt loam intergrade (fine-silty mixed thermic Typic Hapludalf - fine-silty mixed thermic Typic Fragiudalf), characterized by high silt and low clay content, low cation exchange capacity, and a variably developed fragipan at 90-120 cm (Bandaranayake et al. 1996). Sycamore were established on three plots at 1.2 m within-row by 2.4 m between-row spacing and corn was established on three plots using typical reduced tillage establishment methods.

Crop management practices used in the establishment and production of the row crops, tree crops, and switchgrass were chosen to represent best management practices for practical economic production of the crops. This approach was chosen to replicate methods that would be employed by typical biomass crop producers and to identify modifications of these practices that could provide increased environmental benefits through biomass crop production. Silvicultural methods practiced for each SRWC included herbicidal control of competing vegetation, except for the treatment at the Alabama A&M site where the cover crop was used to compare with treatments using chemical weed control. Fertilizer was added to the row crops at typical rates for the different crops. Only the cottonwood at Mississippi State University received nitrate application (58 kg/ha) in the first year; at the other two sites it was assumed that residual N was sufficient to supply N needs for the first year of the rotation. All tree crops received broadcast application of phosphate, potassium, and lime on an individual basis as identified by soil tests to ensure adequate fertility levels. In year two the SRWCs at all three sites received N fertilizer additions (cottonwood 58 kg/ha, sweetgum 84 kg/ha, and sycamore 135 kg/ha) (Thornton et al. in review).

At each of the three sites, the experimental treatments were enclosed within artificial watersheds by using soil from outside the plot areas to construct 0.5 m berms surrounding each treatment. The berms, which were seeded to grass to minimize their contribution to sediment transport from the individual plots are pentagon shaped with a 0.5 m flume located at the downslope point of the triangular shaped portion of the pentagon arm of the berm. Each flume was equipped with a flow proportional sampler and flow meter. The flow meters provide continuous estimates of the volume of runoff at each flume and the flow proportional sampler collects water samples during storm events on a flow proportional basis. Samples from rainfall events producing measurable runoff are typically collected within less than 12 hours after cessation of precipitation. Sediment loss and chemical transport in the runoff are determined for each sample and treatment.

Four pan lysimeters (91 x 61 x 8 cm, L x W x H) were used to collect leachate to estimate treatment effects on groundwater quality and quantity. At the Alabama and Tennessee sites the lysimeters were installed at a depth of 1.5 m. This depth was determined to be a practical limit for the rooting depth of SRWC crops at the two sites. At the Mississippi site lysimeters were installed to a depth of 0.8 m; this depth was chosen to avoid potential problems with groundwater reflux at the site. Lysimeters were installed into the upslope faces of the excavated soil pits to minimize the zone of soil disturbance for the lysimeters.

Surface and groundwater quality samples from all sites were analyzed by a central laboratory to increase comparability of data across sites. Colometric procedures were used for the analysis of nitrate and ammonium and ICP analysis was used for Ca. Mg, K, Na, B, Fe, Mn, Cu, Zn, Al, and bioavailable P.

Baseline soil physical properties including aggregate stability, porosity, bulk density, hydraulic conductivity, and penetrometer resistance and soil chemical properties were determined using standard methods. These data will be compared with post-treatment samples to identify chances in physical properties over the crop rotation. Changes in build up or release of nutrients and/or loss of soil organic matter are being compared for pre- and post-harvest of the woody crops.

Results and Discussion

Tree survival and growth in the first year after establishment were considered to be excellent; average tree heights in October of 1995 were 5.4 m for cottonwoods, 1.3 m for sweetgum, and 1.6 m for sycamore. Complete canopy closure was attained on the cottonwood plots at the Mississippi site during the early part of the second growing season. Early indications are that as tree crops and switchgrass provide soil cover that nutrient and soil losses decrease. Results to date are summarized in the following subsections.

Runoff

At the Alabama site, the sweetgum treatment had a statistically greater runoff amount in the spring of 1995 and exhibited higher runoff in the other seasons. This site also had the highest ratio of runoff to total rainfall; 48% of the precipitation falling on the soil left the sites as runoff. Thornton et al. (1996) attributed this high runoff rate to site specific characteristics such as the greater slopes at this site, the higher amount of rock fragments on the soil surface, a higher soil clay content, and the more exposed soil surface (particularly on the tree crop with no cover crop). During the period of establishment, runoff and sediment transport from the switchgrass plots at the Alabama site were comparable to that from the tree crop sites without a cover crop (Fig. 1). Over time, the sediment losses associated with rainfall events at the Alabama site reflected the soil cover provided by the individual crop treatments; after the corn crop, sweetgum with a cover crop and switchgrass began to grow in the spring, the sediment losses decreased significantly (Fig. 1). Initial identification of the benefits of cover crop strips between rows for runoff and erosion control can provide management tools to minimize both on-site and off-sites effects. Pimental and Krummel (1987) point out the importance of maintaining a vegetation cover on the soil; removal of vegetation increases runoff rates by 10-102 times above that from vegetated lands. The data from this site showing most of the sediment transport occurring during the year of establishment supports their observation that most of the erosion associated with managed forest systems occurs in the first few years.

At all sites, most of the runoff was found to occur during rainfall events and to

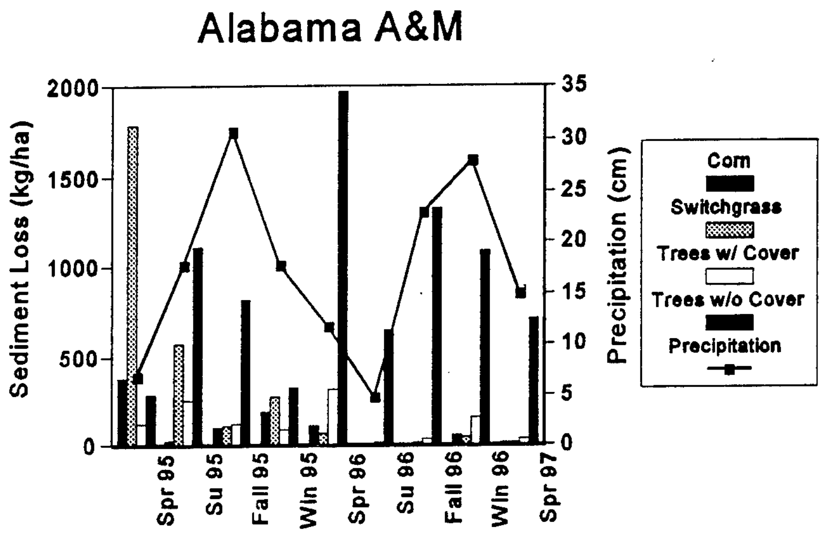

Figure 1. Sediment yields by season (kg/ha/season) for the four treatments at the Alabama site, spring 1995 through spring 1997. Precipitation volume for each seasonal period is also depicted.

correspond to the intensity of the rainfall event. For example, at the Mississippi site runoff volume was greatest between cotton and cottonwood during two closely spaced runoff events (Fig. 2). Sediment losses from the cottonwood plots and cotton plots were low during the first growing season with sediment losses from the cottonwood plots dropping to negligible levels after canopy closure early in the second growing season (Fig. 2). When data from the first and second growing seasons were compared, there was no significant difference in overland flow, infiltration, or evapotranspiration between cotton and cottonwoods (Joslin and Schoenholtz 1997). At the Tennessee site, sediment losses in runoff from the sycamore plots were generally low during the first year of establishment (Fig. 3). Sediment losses from the no-till corn particularly in the fall of 1995 reflected removal of the soil cover with removal of the majority of the corn stalks and stubble as silage. Comparable levels of erosion for corn and sycamore in the second year of growth are indicative of the similarity of soil cover at the site.

Data from the next two years will show whether the cover crop established between rows at the Alabama site becomes a competitor for nutrients as the sweetgum trees grow and extend their rooting systems into the area between rows. Data from this site will also show whether as the sweetgum trees increase their canopy closure if the differences in runoff and erosion between treatments with and without cover crops are decreased. The quantified results from these plot scale studies are providing the actual

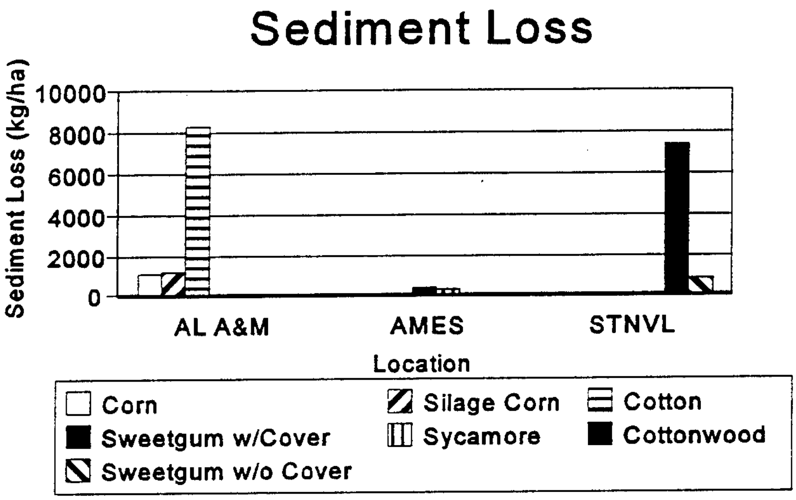

Figure 2. Comparison between crop treatments across the three sites with respect to sediment yield (erosion) for spring 1995 through spring 1997 (kg/ha/2.25 years)

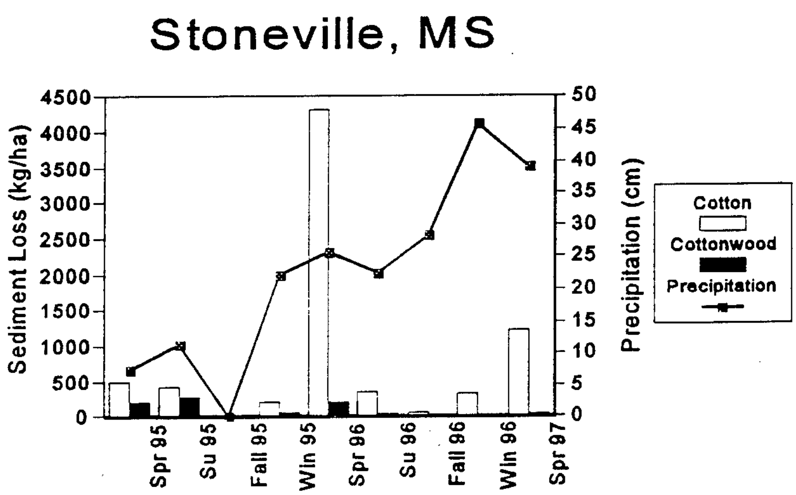

Figure 3. Sediment yield by season (kg/ha/season) for cotton and cottonwood at the Stoneville, MS site, spring 1995 through spring 1997. Precipitation volume for each seasonal period is also depicted.

data to validate projections made in 1987 by Pimental and Krummel in assessing the resource costs to the environment from conversion of agricultural lands to woody and herbaceous biomass crop production. Kort et al. (1997) presented data that showed that erosion from sod crops is almost nil compared to row crops. If the data from the Alabama switchgrass sites continues to show that runoff and sediment transport on a site with 6 percent slope is minimal after the first year of establishment, this study supports McLaughlin et al. (1994) conclusions to show that with proper establishment techniques biomass crops can provide similar environmental benefits to grass crops grown on CRP lands. This can increase the acceptance of production of these crops using proper management techniques on CRP lands.

Nutrient Movement

From 1995 through spring of 1997, nitrate transport was greater from the row crops than from either switchgrass or the woody crops (Fig. 4). Initial results from the runoff studies showed that most of the nutrient transport occurred in the spring following

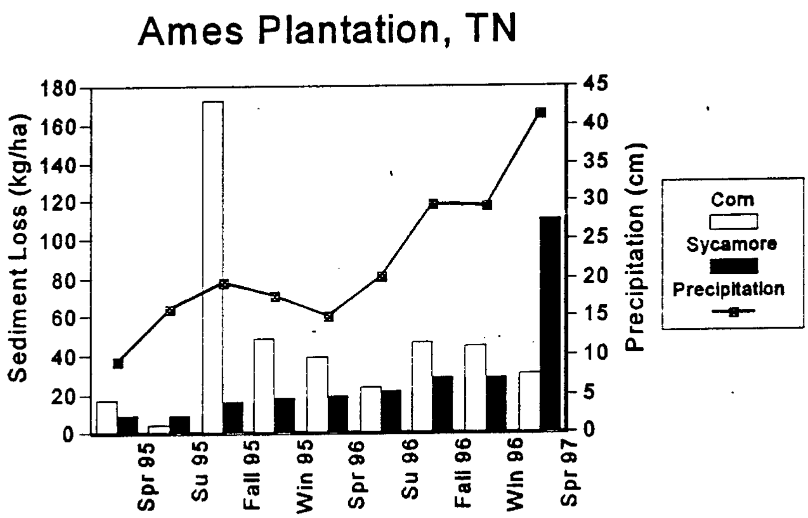

Figure 4. Sediment yield by season, spring 1995 through spring 1997. Precipitation volume for each seasonal period is also depicted.

fertilizer applications (Green et al. 1996, Thornton et al. 1996, Tolbert et al. 1997). During the 1995 - spring 1996 time period, there was significantly greater export of nutrients from the crop plots at all sites and from the switchgrass plots at Alabama. The higher loss of N from the switchgrass plots in the spring of 1995 was related to the slow establishment of this warm-season grass following spring planting and the greater erosiveness of one of the plots. Once the switchgrass was established, nutrient losses following application of 68 kg of N per ha dropped to losses of only 1 kg of NO_3^- and NH_4^+ per ha (Thornton et al. 1996). Use of a winter cover crop on the corn plots at the Tennessee site during the winter of 1995 reduced the nutrient transport from these plots compared to that from the sycamore plots. This use of a cover crop to maximize soil stability and minimize nutrient losses support Pimental and Krummel's (1987) conclusion that maintenance of a vegetative cover is essential to minimizing soil, organic matter, and nutrient losses.

Runoff losses of nitrate at the Tennessee site were higher from the no-till corn than from the sycamore plots. Over the total sampling period, nitrate losses in runoff reflect the timing of fertilizer application in the spring and transport from the site prior to utilization by the tree and row crops. Nitrate leaching from the no-till corn plots at the Tennessee site was accompanied by two to three-fold increases in calcium, magnesium, and potassium losses below a depth of 1.4 m. Makeschin (1994) found when comparing tree crops and agricultural plots that the soil solution nitrate leaching was reduced by 50 percent by the third year of tree crop growth. With only two years of data on tree crop growth at a rotation of at least 10 years, it is not yet possible to quantitative differences in response of the tree and switchgrass crops through time and with changes in management practices to correspond to changes in crop structure. It is important for this study to

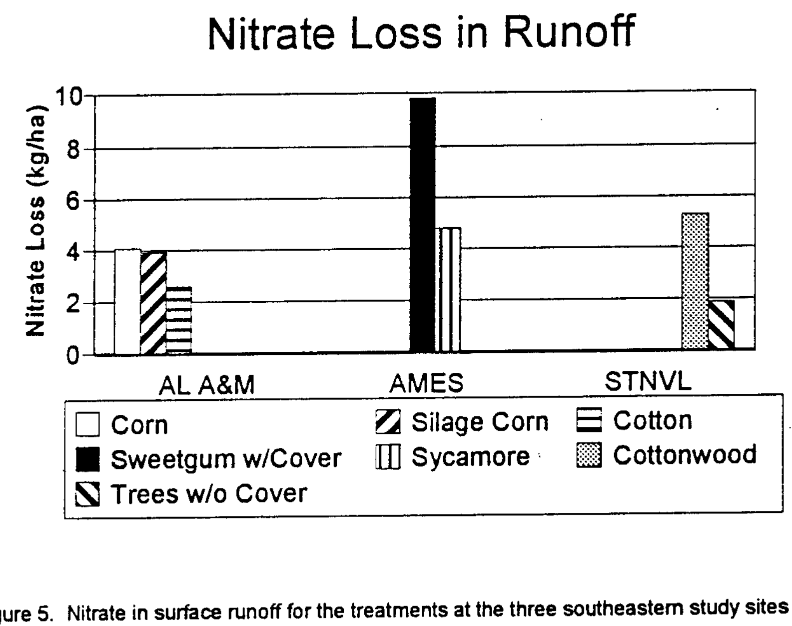

Figure 5. Nitrate in surface runoff for the treatments at the three southeastern study sites for the first 2.25 years of the study (kg/ha/2.25 years)

quantify these differences in crop growth and management practices to inform future plantings of biomass crops to provide environmental benefits and well as maximize yields of these crops.

This 3-site, plot-scale study is providing the basis for a watershed study established ion a coastal plain sites in eastern South Carolina in spring 1997. This study is building upon the design of the plot-scale study to compare environmental responses to woody crop production at a larger scale to determine if it is possible to project environmental benefits of biomass crop development at a plot-scale to production at a landscape scale. Sub-watersheds of 10 - 30 ha have been established using traditional commercial-scale management practices. The watersheds were bermed in a manner similar to the plot-scale studies. Existing drainage ditches were incorporated into the experimental watersheds to monitor surface water runoff and nutrient transport. The sub-watersheds are fitted with weirs, standpipe recorders, and flow-proportional monitors for event water quality monitoring and with tension lysimeters to monitor subsurface water movement. The tree crops under study are replicate watersheds of sweetgum and sycamore planted either with or without a cover crop. The watersheds planted with a cover crop will change management techniques after the trees have approximated canopy closure to address the potential to retain and manage water availability to maximize tree crop growth during low rainfall periods. This is particularly important for coastal plain soils which are high in sand content and are well drained. These soils retain only an approximate 7 day water storage that can support continued tree growth. The ability to provide adequate moisture for tree crop growth while minimize nutrient leaching is an important environmental aspect of this study.

Research Directions

In addition to the six sub-watersheds, two watersheds of approximately 600 ha each have been instrumented to address landscape scale environmental effects of broad-scale conversion of agricultural lands to woody crop development. One of the watersheds is being totally planted to woody crops while the other will remain in a combination of woody crops and traditional agricultural crops. The data from these two watersheds will be compared and along with the data from the sub-watershed sites will be used to parameterize hydrologic and nutrient models to predict water and nutrient movement associated with biomass crops at landscape scales. Data will be compared with that from the plot-scale studies to determine differences in scale, tree crops, and for different soil types to provide future guidance on how to establish, maintain, and ultimately harvest biomass crops to provide environmental benefits while providing maximum biomass crop yields.

The cottonwoods established at the Mississippi site will be harvested in October 1997. Post-harvest soil physical parameter measurements will be taken following harvest for comparison with pre-planting and pre-harvest measurements to determine differences in the soil characteristics noted in the materials and methods section. Soil carbon and soil nutrient availability will be compared with the pre-planting samples. Both above-ground and below-ground biomass will be determined. Following harvesting, the stumps will be removed from half of each of the plots and the part of the plot with the stumps removed will be cultivated and prepared for cotton planting in the spring. The other half of each plot will remain fallow until spring and will be prepared using no-till drilling for cotton crop establishment. A berm will be established the length of the plot and weirs and water quality monitoring equipment established on each half of the plots. Measurements of runoff, erosion, and nutrient transport for the different treatments will be sampled as for the initial study to quantify differences in site preparation and crop re-establishment. This part of the study at the Mississippi site is designed to quantify changes in soil physical structure and chemistry with conversion back to agricultural crops and to determine the longer-term effects on soil carbon from site preparation methods and return to agricultural crop production. This part of the study will also address the potential benefits for nutrient availability for subsequent crops and for increased cotton root penetration into the deeper soil layers from having the cottonwood stumps and roots left in place. (The site traditionally develops a plow-pan layer during the growing season that is impenetrable to cotton roots.) Data from this aspect of the study will identify for farmers how biomass crops can be incorporated into their farm management to provide land use benefits, alternative sources of income, and environmental benefits for soil and water quality.

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