The water quality and quantity effects of biofuel operations in pine plantations of the southeastern USA

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Abstract Working alongside operational trials, a comprehensive research programme was developed to evaluate sustainability, life-cycle analysis, soil productivity, wildlife, and water resource impacts. The hydrology field studies consist of three sets of forested watersheds, each with mid-rotation pine reference, switchgrass (*Panicum virgatum*) interplanted, typical silvicultural, and switchgrass only sub-watershed treatments. Two of the three locations will also have a woody biomass understory treatment. Each of the 14 sub-watersheds is instrumented and collecting detailed hydrology, water quality, and climate data. While these on-going, detailed studies are necessary for understanding processes such as field evapotranspiration and nutrient cycling, three shorter-term, complementary studies of intercropped sites were completed: groundwater table response and soil compaction in artificially drained blocks in North Carolina; soil moisture response and soil compaction in an uplands site in Mississippi; and sediment production across operational tracts in Mississippi and Alabama. The results of these three studies are presented, along with the large watershed plan and status, and implications under possible climate change scenarios.

Key words silviculture; switchgrass; intercropping; biofuels; sustainability; erosion; evapotranspiration

INTRODUCTION

Biofuel energy will likely play an important role in mitigating climate change, but the total environmental cost must be quantified. Many biofuel scenarios require extensive irrigation, reducing their viability in water-limited regions. Although forest-based biofuel systems are not irrigated, productivity and operational costs have made them less feasible than agricultural systems. Dedicated bioenergy crop interplanting in loblolly pine (*Pinus taeda*) sawtimber plantations in the southeastern USA may reduce many of these problems without the environmental impact associated with irrigated annual crops.

A multi-scale study has been implemented to evaluate the environmental consequences of biomass cultivation in managed forests. Designed to be a comprehensive, flexible research programme, it will evaluate possible biomass production scenarios that could affect millions of acres of forest in the southeastern USA. Designing a study based on production methods that are still subject to technical, economic and regulatory uncertainties is difficult, so treatments and methods were selected to not only represent the best available knowledge but also span a range of sites, slopes, and management intensities. The study consists of sustainability, life-cycle analysis, soil productivity, wildlife, and water resource components.

The broad project objectives are:

– Quantify the hydrology of different energy crop production systems in watershed scale experiments on different landscapes in the southeast USA.
– Quantify the nutrient cycling and export of energy crop production systems in watershed scale experiments to determine the impact of these systems on water quality.
– Evaluate the impacts of energy crop production on soil structure, fertility and organic matter content.
– Evaluate the response of flora and fauna populations and habitat quality to energy crop production systems.
– Quantify the production systems in terms of bioenergy crop yield *versus* the energy and economic costs of production.
– Develop watershed- and regional-scale models to evaluate the environmental sustainability and productivity of energy crop and woody biomass operations.

– Develop and evaluate best management practice guidelines to ensure the environmental sustainability of energy crop production systems.

The focus of this report is the water quality and quantity study component, which consists of large watershed studies and shorter-term complementary studies.

Watershed studies

The hydrology field study consists of three sets of forested watersheds established in North Carolina, Mississippi and Alabama (Fig. 1). Each study site includes at least four small, operational-scale sub-watersheds that are instrumented to provide data on precipitation, stream discharge, weather, groundwater and water quality.

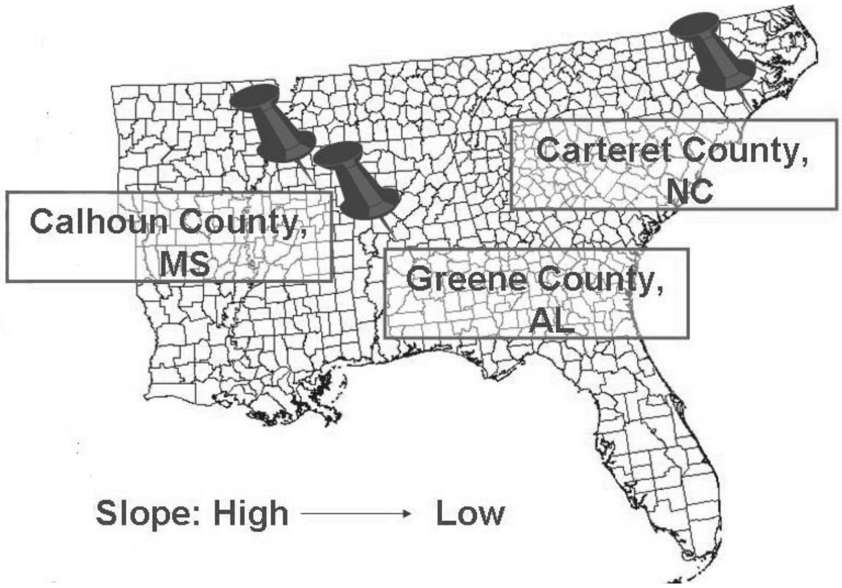


Fig. 1 Location of forested watersheds for pre-treatment and treatment studies.

Equipment installation is complete, and pre-treatment data are being collected and analysed. Biomass treatments that will be applied to the sub-watersheds will represent a spectrum of biofuel management intensities:

– typical pine plantation, about 15 years old;
– young pine, high value timber regime;
– young pine, woody biomass removal;
– young pine, interplanted with switchgrass; and
– switchgrass only.

COMPLEMENTARY STUDIES

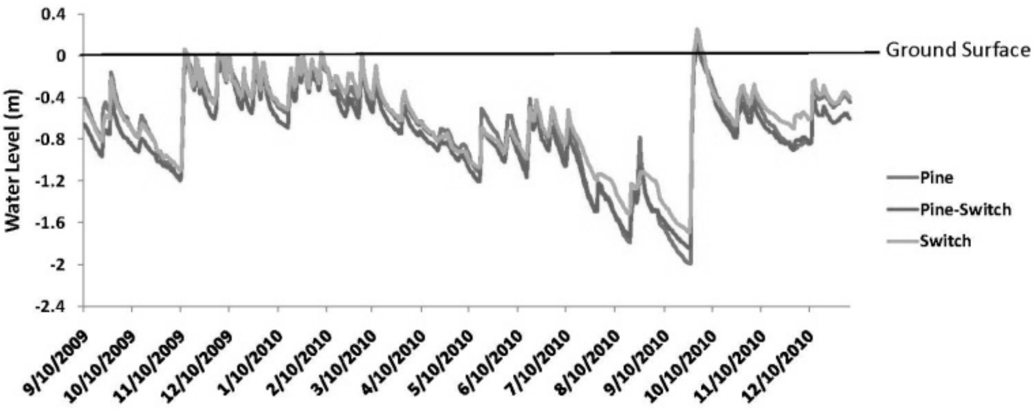
While these ongoing, detailed studies are necessary for understanding processes such as field evapotranspiration and nutrient cycling, shorter-term, complementary studies of intercropped sites were initiated.

Small-scale field plots This research uses 2-acre field plots, replicated in three blocks, within the same management unit, to begin to quantify the impacts of intercropping stands on hydrology and water quality, soil nitrogen dynamics, and soil physical and hydraulic properties, and carbon dynamics. Additionally, collected data will be used to parameterize the DRAINMOD-FOREST model, which will be extended to model forest productivity, hydrology and biogeochemistry on the North Carolina watershed sites.

The site, located in Lenoir County, NC, has deep, poorly drained, moderately permeable sites, and is artificially drained with ditches approximately every 100 m. Ditches bound the treatment plot, randomly located in the replicated blocks. The treatments are:

– loblolly pine only with biomass-in-place,
– loblolly pine-switchgrass intercropped with biomass-in-place, and
– switchgrass only with biomass removed.

Groundwater level is recorded in wells located at the middle of each plot and 1 m from the ditch edge. Water quality samples are collected monthly and more frequently after fertilization. Measurements of soil physical and hydraulic properties are conducted before and after field operations. Soil N mineralization and nitrification measurements are conducted *in situ* using a sequential incubation technique and by laboratory methods.



MEAN DAILY GW LEVEL FROM GROUND SURFACE (M)			
	Pine	Pine-Switch	Switch
Sept/09 to Nov/09	-0.596	-0.734	-0.610
Dec/09 to Mar/10	-0.305	-0.397	-0.271
Apr/10 to Aug/10	-0.941	-1.025	-0.891
Sept/10 to Nov/10	-0.852	-0.873	-0.719
Dec/10 to Jan/11	-0.545	-0.647	-0.438

Fig. 2 Groundwater level from all treatments in Block 1 from 9 October 2009 to 1 April 2011 at Lenoir County small watershed study.

Based on the data, the pine-switchgrass treatment has the deepest mean daily water level among the treatments across all replicate blocks (each block consists of four 20 × 20 plots), especially during the growing season, although the differences among the treatments are not very high. Statistical analysis of the data at $p < 0.05$ shows that there is no significant difference on the mean daily groundwater level among the treatments ($p = 0.98$).

There is no distinct seasonal pattern for organic-N concentration. In general, the concentration across treatments is less than 2.0 mg L^{-1}, and for the most part less than 1 mg L^{-1}. Overall, there is no significant difference among treatments on the mean concentration of organic N. Pine treatments tend to have higher ammonium-N concentration, but there is no significant difference among treatments regarding the mean concentration of ammonium-N.

Nitrate-N, orthophosphate, and total organic carbon (TOC) concentrations showed a seasonal pattern, with concentrations higher during the dormant seasons, but no significant difference in the mean concentrations among treatments.

Table 1 Correlation (p values) among water quality constituents and site or treatment effects, October 2009–December 2010.

Effect	ON	NH_4^+-N	$NO_3^- + NO_2^-$-N	OPO_4-P	TOC
Treatment	0.9137	0.2205	0.0917	0.1447	0.3857
Well type	0.6718	0.0343	0.7695	0.4572	0.0037
Depth	0.0031	0.9298	0.0163	<0.0001	0.0001
Month	0.0218	0.6112	0.0004	<0.0001	<0.0001

To summarize, preliminary analysis of the data shows no significant difference ($\alpha = 0.05$) of the mean daily groundwater level among treatments (Table 1). The differences among the treatments on monthly groundwater concentrations of organic N, ammonium-N, nitrate + nitrite-N, orthophosphate-P and TOC are also not significant.

Soil moisture In order to estimate field evapotranspiration rates of intercropped switchgrass plots, a short-term soil moisture study was conducted over the spring and summer of 2010. Two treatments were used on the manipulated site – an established switchgrass plot, and a suppressed understory plot – in a 5-year-old pine plantation. The treatments were replicated twice per block, and randomly arranged in three blocks of four 20 × 20 plots. The plots are in similar soil and slope gradients, and all plots in a block were laid out along a contour line to minimize differences in uphill drainage. Reference plots were established in a nearby plantation with similar-aged pine stands and a native understory.

The site is in Clay County, MS. The soils have a fragipan layer at about 1.5 m, with loam and clay loam above it. The infiltration and rooting limitation of the fragipan layer allowed an accurate accounting of soil water and ensured that the pine and switchgrass are using the same source water – a confounding factor in other intercropping studies.

Tubes for an AP moisture probe (http://www.aquapro-sensors.com/) were installed in threes – mid-plot and in the pine row on either side. Measurements were taken three times per week at depths from 20 cm below the soil surface to the fragipan layer. Soil compaction was to be measured before and after equipment entries, but the very dry late summer dried and cracked the soil around the tubes making pre-harvest measurements unusable.

The preliminary results (Fig. 2) indicate that the soil moisture under the switchgrass sites is much more similar to the plots with suppressed vegetation than that of natural understory, implying a water yield increase from the replacement of natural understory with switchgrass. However, the switchgrass has not reached full site occupancy and maturity, and its ET will continue to increase. Some literature reports show switchgrass ET at maturity to be quite high, and subsequent monitoring will quantify this relative change over time.

Sediment survey A field survey was conducted in Mississippi and Alabama to estimate the sediment impact of intercropping switchgrass (*Panicum virgatum*) in loblolly pine plantations. Intercropped tracts with riparian buffers were evaluated for erosion potential, and sites with little slope and very stable soils were removed from the selection set. The study was designed to look for sediment problems, i.e. when and where they were most likely to occur. In addition to selecting from the sites with the highest erosion potential, the survey was conducted before the switchgrass was mature, and in the late spring, after a very active rainfall season but before the summer growing season.

Nine sites totalling ~280 hectares were randomly selected from the remaining management tracts. The intercropped tracts had switchgrass beginning its second growing season under 4- to 6-year-old pine. The switchgrass rows closest to each riparian buffer were surveyed for sediment incursions due to biofuel operations. Location, estimated sediment incursion length, sediment depth, soil texture, sediment barriers and stream connectivity were recorded for each sediment incursion point (Fig. 3). Each point was mapped, the delivery pathway delineated and delivery potential determined.

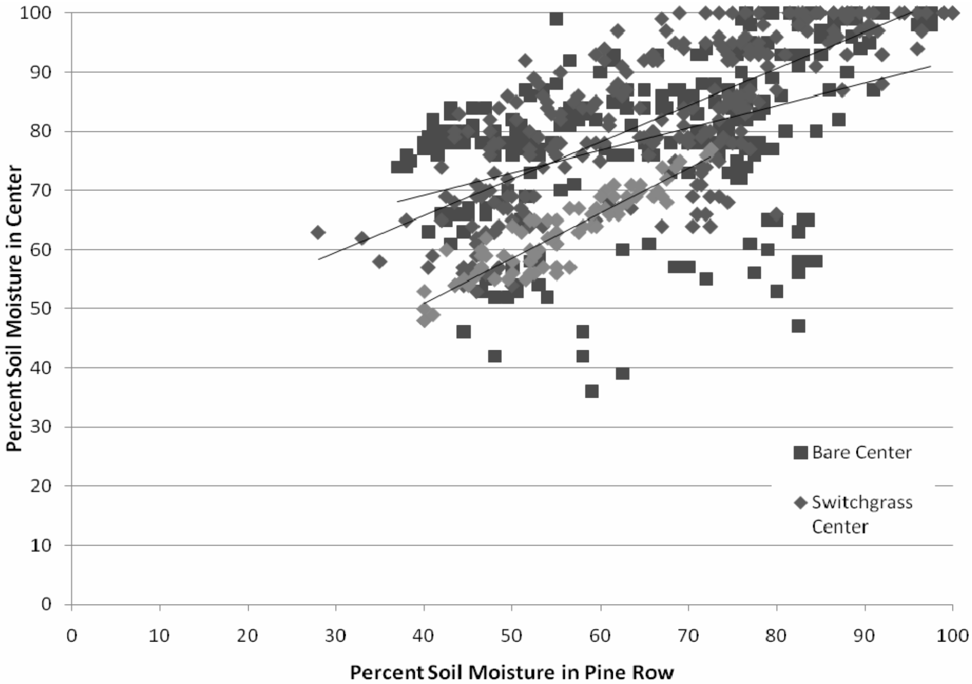


Fig. 2 Soil moisture values by plot at a depth of 0.6 m.

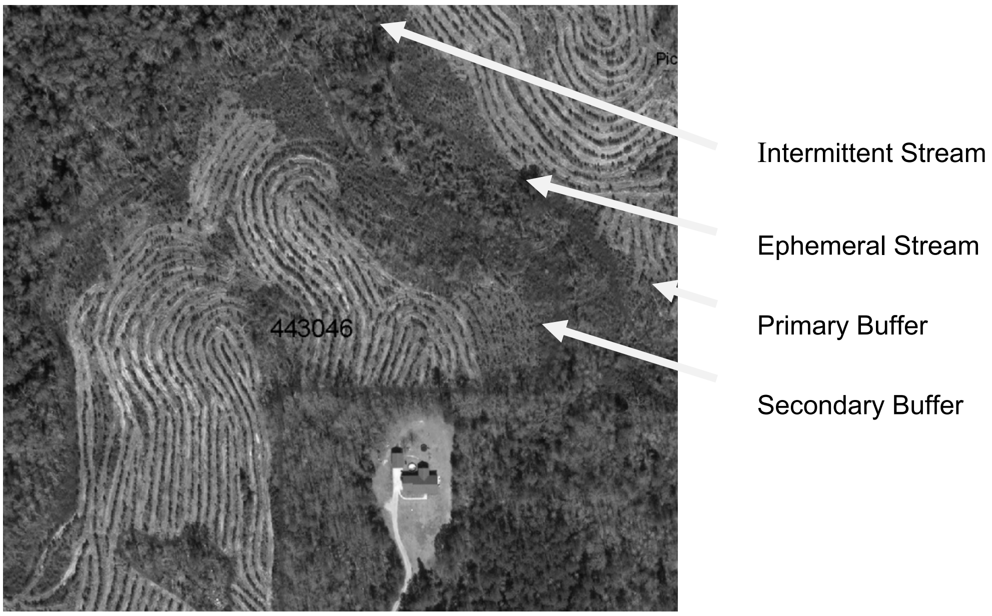


Fig. 3 Example site layout and sediment path delineation.

Most of the sites were found to have not only a primary riparian buffer established to protect water quality during silvicultural operations, but a secondary buffer. The secondary buffer consisted of pine plantation rows that the biofuel operator chose not to plant in switchgrass. This additional erosion protection was not established *a priori*, but left at the discretion of the biofuel operator at the time of site preparation and planting. Small berms are created along the edges of the switchgrass rows as part of the intercropping process, and this berm, lying along the pine beds, provided additional protection by limiting movement of any soil eroded during planting .

The total distance from the last planted switchgrass row to a perennial stream was mapped, and divided up into four segments. In the nine tracts, 31 sediment incursions were noted.

Preliminary analysis indicates that the average travel distance from the incursion point to a perennial stream are 255 m, with the components averaging:

- secondary buffer (biofuel): 20 m,
- primary buffer (existing silvicultural): 17 m,
- ephemeral stream: 93 m,
- intermittent stream: 125 m.

Of the 31 incursions, four were found to have the potential to deliver sediment to a perennial stream. Three sites had some obstructions, but still had the potential to deliver sediment to perennial streams under high flow conditions. There was no evidence of ongoing problematic erosion, but sediment deposition was observed in the riparian buffer. The fourth site was a road crossing that did show direct delivery into a small stream. Logging roads are often grassed by broadcast seeding after harvest, but this had been closed by planting with switchgrass and was actively eroding down the planting rows and into a stream crossing. This action violated operational policy but since it is expected to stabilize with switchgrass growth and spread, remediation is not recommended.

While there was at least one incident of increased sediment delivery to an active stream, the combination of site planning, effective operating practices and good ground decisions appeared to be protective. Some incursions will be revisited, but preliminary analysis appears to show that intercropping can be done operationally without an inherent increase in sediment.

CONCLUSIONS

The detailed watershed studies will give us precise numbers, but early results show little change in water quantity and quality from intercropping switchgrass in an operational pine plantation.