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Bio-energy Feedstock Yields and their Water Quality Benefits in Mississippi

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Abstract. *Cellulosic and agricultural bio-energy crops can, under careful management, be harvested as feedstock for bio-fuels production and provide environmental benefits. However, it is required to quantify their relative advantages in feedstock production and water quality. The primary objective of this research was to evaluate potential feedstock yield and water quality benefit scenarios of bio-energy crops: Miscanthus (Miscanthus-giganteus), Switchgrass (Panicum virgatum), Johnsongrass (Sorghum halepense), Alfalfa (Medicago sativa L.), Soybean {Glycine max (L.) Merr.}, and Corn (Zea mays) in the Upper Pearl River watershed (UPRW), Mississippi using a Soil and Water Assessment Tool (SWAT).*

The SWAT model was calibrated (January 1981 to December 1994) and validated (January 1995 to September 2008) using monthly measured stream flow data. The calibrated and validated model determined good to very good performance for stream flow prediction (R2 and E from 0.60 to 0.86). The RMSE values (from 14 m3 s-1 to 37 m3 s-1) were estimated at similar levels of errors during model calibration and validation. The long-term average annual potential feedstock yield as an alternative energy source was determined the greatest when growing Miscanthus grass (373,849 Mg) as followed by Alfalfa (206,077 Mg), Switchgrass (132,077 Mg), Johnsongrass (47,576 Mg), Soybean (37,814 Mg), and Corn (22,069 Mg) in the pastureland and cropland of the watershed. Model results determined that average annual sediment yield from the Miscanthus grass scenario determined the least (1.16 Mg/ha) and corn scenario the greatest (12.04 Mg/ha). The SWAT model simulated results suggested that growing Miscanthus grass in the UPRW would have the greatest potential feedstock yield and water quality benefits.

Keywords. Biofuels, feedstock yield, water quality, SWAT, watershed.

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Introduction

The CO_2 emissions due to energy use are projected to increase on average by 1.5 percent per year from 2002 to 2025 (US/DOE, 2004). The impact of greenhouse gases such as carbon dioxide (CO_2) on the environment in combination with the present need for biofuels have urged a genuine concern regarding our increasing research need on cellulose or crop based biofuels and their environmental effects, such as on water quality. Bio-energy crops such as cellulosic and agricultural crops can have distinct water quality advantages associated with their production and use. Bio-energy crops offer a wide range of environmental benefits and can have a positive environmental impact. One environmental benefit associated with bio-energy crops is reduced soil erosion by improving surface water quality.

Giant Miscanthus (Miscanthus x giganteus) is a tall perennial grass that is being grown experimentally in numerous countries in the world. Miscanthus could be a primary feedstock source for the many bio-fuel industries. Miscanthus grass has been evaluated at Mississippi State University and in different parts of the world over the past 5-10 years as a new bio-energy crop. Since the plant can get as tall as 4 m, it can yield up to 50 tons per ha per year (Baldwin, 2010). The current research in miscanthus suggests that this novel energy crop deserves serious investigation as a possible bio-fuel crop for the United States along with switchgrass, johnsongrass, alfalfa, soybean, and corn.

Switchgrass has been identified by the Dept. of Energy (DOE) as a primary crop for development because of its potential for high bio-fuel yields and its ability to grow on marginal cropland without intensive management. A recent review of the initial DOE program to evaluate and develop switchgrass as a bio-energy crop has shown its potential as an alternative to corn for bio-fuels production. In addition, the energy ratio is more favorable for switchgrass than for corn (McLaughlin et. al., 2005). One promising strategy to help significantly reduce sediment, surface runoff, and nutrient loading into Mississippi streams, tributaries, and reservoirs is to plant perennial warm season grasses such as switchgrass in selected locations within watersheds. A recent study and analysis in Kansas shows that the use of switchgrass resulted in reduced soil erosion from rainfall as well as general reductions in nutrient loss in runoff and subsurface flow versus all conventional commodity crops (King et al., 1998). Switchgrass is also regarded as a highly promising energy crop with an average energy yield of approximately 260.8 GJ per ha at a production level of approximately 25 Mg per ha per year (Baldwin, 2010) in the southeast U.S.

Plant growth models in conjunction with hydrologic models such as SWAT (Arnold et al., 1998) are often used to investigate potential crop yields and water quality effects due to land use change. Gassman et al. (2007) presented a comprehensive literature review of the SWAT model applications, which demonstrated that the SWAT model can be a useful tool for assessing the effects of watershed management on hydrology, crop yield, and water quality. However, the majority of these applications considered only hydrology and water quality. It has yet to compare bio-energy crop yields to bio-fuels production in regards to water quality benefits through a reduction in sediment yield which carries pollutants. The objective of this research was to evaluate feedstock yield and water quality benefits of bio-energy crop scenarios (Miscanthus, Alamo switchgrass, Johnsongrass, Alfalfa, Soybean, and Corn) at the watershed scale.

Materials and Methods

Study area

This research study was focused at the UPRW, which is located in east-central Mississippi. The UPRW is comprised of ten counties (Choctaw, Attala, Winston, Leake, Neshoba, Kemper, Madison, Rankin, Scott and Newton), and covers 7,588 km^2 (Fig. 1). The watershed consists of woodland (72%), grassland (20%), urban land (6%) and others (2%). The fine-sandy-loam and silt-loam textured soils are predominant soil types in this watershed.

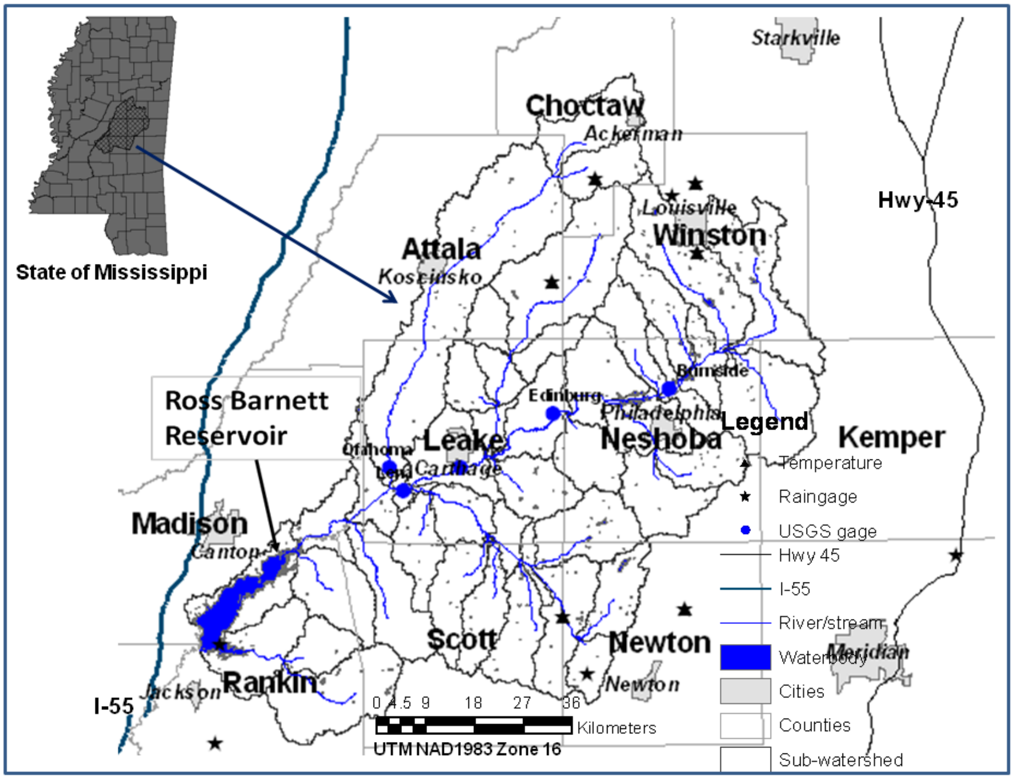

Figure 1. Location map of Upper Pearl River watershed in east-central Mississippi showing USGS streamflow gages and climate stations.

SWAT Model

The SWAT model as described by Arnold (1998) is physically based, operates on a continuous daily time step, is watershed scale, and uses pollutant-loading models developed to simulate long-term runoff, sediment, nutrients, pesticide transport, and crop yield from agricultural watersheds. The SWAT model uses hydrologic response units (HRUs) based on unique land cover, soil, and topographic conditions. The HRUs are necessary to accurately consider the possible effects of spatial and temporal variations in parameters on hydrological processes and sediment, nutrient, and crop yield simulations. The hydrology component of the model calculates a soil water balance at each time step based on daily amounts of precipitation, runoff, evapo-transpiration, percolation, and base flow. Simulations are performed at the HRU level and summarized in each sub-watershed. The simulated variables (water, sediment, nutrients, and other pollutants) are routed through the stream network to the watershed outlet. The SWAT model incorporates the effects of weather, surface runoff, evapo-transpiration, crop growth, irrigation, groundwater flow, nutrient loading, pesticide loading, and water routing, as well as the long-term effects of varying agricultural management practices (Neitsch et. al., 2005). In the hydrologic component, runoff is estimated separately for each sub-watershed of the total watershed area and routed to obtain the total runoff for the watershed. Runoff volume is estimated from daily rainfall using modified SCS-CN and Green-Ampt methods. Due to input data availability, the SCS-CN method was adopted in this study. The Erosion Productivity Impact Calculator (EPIC) model was added in the SWAT model to account for the variation in annual crop growth. SWAT assumes that all heat above the base temperature accelerates crop growth and development. Crop growth will only occur on those days where the mean daily temperature exceeds the base temperature. SWAT monitors the heat unit accumulation for a given day (Neitsch et. al., 2005).

Model Input

The SWAT model has been extensively applied for stream flow modeling (Vache et. al., 2002; Varanou et. al., 2002; Gosain et. al., 2005; Parajuli 2008). The model requires input of Digital Elevation Model (DEM) data, land use, and soils, as well as a time series of climate data such as daily precipitation and temperature. The SWAT model uses various sets of geospatially referenced data to create layers of information that satisfy the necessary input parameters. The United States Geological Survey (USGS, 1999) 7.5-minute (30m x 30m) DEM was used to delineate watershed boundaries and topography. The State Soil Geographic Database (STATSGO) was used to create a soil database (USDA, 2005). The cropland data layer (USDA/NASS, 2008) was used to develop land use data for the watershed. The model inputs climate data from all available weather stations (NCDC, 2009) from ten counties (Choctaw, Attala, Winston, Leake, Nesobha, Kemper, Madison, Rankin, Scott and Newton).

The model inputs climatic data from eleven (Ackerman, Canton, Carthage, Forest, Gholson, Kosciusko, Louisville, Newton, Philadelphia, Ross Barnett Reservoir and Walnut) weather stations (NCDC, 2009; Fig. 1). The SWAT model requires daily values of precipitation, maximum and minimum temperature, solar radiation, relative humidity, and wind speed. This study utilized the best available precipitation data, and the maximum and minimum temperature data from all eleven weather stations. Since the solar radiation, relative humidity and wind speed data were not available from the watershed weather stations, the SWAT model generated those data for the entire model simulation period. The SWAT model includes the WXGEN weather generator model (Sharpley and Williams, 1990) to generate climatic data or to fill in gaps in measured records. This weather generator was developed for the contiguous U.S. and used for the SWAT simulation studies (Neitsch et. al., 2005).

The long-term (1981-2008) annual average daily rainfall for the entire UPRW was estimated about 1,348 mm. The SWAT model uses data from six weather stations (State college, Russell, Forest post office, Meridian, Winona, and Canton). The Forest post office weather station is located inside the watershed whereas the other five weather stations are located from 8 to 45 kilometers away from the watershed.

Bio-energy Crops

This study compared potential feedstock yield of six bio-energy crops using the SWAT model. The SWAT model has developed a detailed crop database for the switchgrass (Alamo), Alfalfa, Johnsongrass, Soybean, and Corn. There is no crop database developed for Miscanthus grass yet in the SWAT model. This study modified the Miscanthus grass database from Switchgrass considering some important crop data as reported by literature (Table 1) including a maximum canopy height of 4.0 m (Scurlock, 1999), a maximum leaf area index of 8.0 m^2/m^2 (Heaton et. al, 2008), and maximum root depths of 2.0 m (Hall R. L., 2003).

Table 1. Comparative crop database parameters used or modified in the SWAT model

Crop	BLAI (m^2/m^2)	CHTMX (m)	RDMX (m)	HVSTI (kg/ha)/(kg/ha)
Alfalfa	4.0	0.9	3.0	0.90
Switchgrass	6.0	2.5	2.2	0.90
Johnsongrass	2.5	3.0	2.0	0.90
Soybean	3.0	0.8	1.7	0.31
Corn	3.0	2.5	2.0	0.50
Miscanthus	8.0	4.0	2.0	0.90

Note: BLAI = maximum leaf area index, CHTMX = maximum canopy height, RDMX = maximum root depth, HVSTI = harvest index.

Pastureland typically includes Bahiagrass (Curt Readus, USDA/NRCS, Pearl area office, 2009, personal communication) in the UPRW. A minor (~2%) land use area of the UPRW covers cropland. Corn, cotton, soybean, peanuts and vegetables are typically grown in the watershed. Typical planting and harvesting dates are April 15 and September 15 for warm-season crops and October 15 and June 15 for cool-season crops. Crop residue is left on the ground between the crop periods. Minimum tillage is typically applied for crop cultivation in the watershed (Curt Readus, USDA/NRCS, Pearl area office, 2009, personal communication). Bio-energy crop production in this study was evaluated on agricultural croplands and pasturelands from two different soil types that typically produce corn, soybeans, and pasture crops.

Model Calibration and Validation Procedures

The SWAT 2005 was manually calibrated by changing critical parameter values, which was suggested to be a preferable method of model calibration (Green and Griensven, 2007). Six widely used flow calibration parameters (Table 2): curve number (CN), soil evaporation compensation factor (esco), base flow alpha factor (ALPHA_BF), surface runoff lag coefficient (SURLAG), ground water “revap” coefficient, and threshold depth of water in the shallow aquifer (GWQMN) were selected based on previous studies (Santhi et. al., 2001; Saleh and Du, 2004; White and Chaubey, 2005; Neitsch et. al., 2005; Gassman et. al., 2007; Parajuli et. al., 2009). Detail model calibration and validation procedures are described in the previous study by Parajuli (2010).

Table 2. Parameters range and final values used in the SWAT model calibration

Parameter	Range	Final Values
Landuse (Curve Numbers)		
Pasture (PAST)	74-86	79
Deciduous forest (FRSD)	70-77	77
Evergreen forest (FRSE)	70-77	70
Mixed forest (FRST)	70-77	73
Urban institutional (UINS)	77-94	92
Wetland forest (WETF)	70-77	77
Soybean (SOYB)	85-90	89
Corn (CORN)	85-90	89
Soil evaporation compensation factor (ESCO)	0-1	0.4
Base flow alpha factor (Alpha_BF)	0-1	0.9
Surface runoff lag coefficient (SURLAG)	1-12	1
Ground water "revap" coefficient (GW_REVAP)	0-1	0.2
Threshold depth of water in the shallow aquifer (GWQMN)	0-5000	1000

Statistical Analysis

This study used the mean monthly flow data collected by USGS at five gage stations. The monthly measured stream flow dataset was divided into a calibration period (1981–1994) and a validation period (1995–2008). Each model performance period includes wet, dry, and normal years, providing representative years for simulating the hydrograph of the UPRW basin. In order to statistically test the accuracy of the calibrated stream flow output, this study employed three popular methods (Parajuli et. al., 2008; 2009): the R^2, E, and root mean square error (RMSE). Monthly model performances were classified as excellent for R^2 or E ≥ 0.90, very good for R^2 or E = 0.75 to 0.89, good for R^2 or E = 0.50 to 0.74, fair for R^2 or E = 0.25 to 0.49, poor for R^2 or E = 0 to 0.24, and unsatisfactory for R^2 or E < 0 (Moriasi et al., 2007; Parajuli et al., 2008; 2009; 2010). The smaller the RMSE, the better the performance of the model, and a value of zero for RMSE represents perfect simulation of the measured data. However, there is no absolute value suggested for RMSE (Moriasi et. al., 2007). Further, the R^2, E, and RMSE were calculated as described by Parajuli (2010).

Results and Discussion

This study utilized a previously calibrated and validated SWAT model using twenty-eight years of monthly measured flow data from the USGS gage stations in the UPRW. The SWAT model-predicted monthly flow reasonably matched measured values during previous calibration and validation studies for the UPRW (Parajuli, 2010). Twenty-eight years of monthly measured stream flow data were used to provide baseline calibration and validation for the SWAT model. The model was calibrated using monthly measured stream flow data from five USGS gage stations within the UPRW from January 1981 to December 1994 and validated using data from the same USGS gage stations from January 1995 to September 2008. The correct amount of moisture uptake by the vegetation and water budget that was removed from the hydrologic system ensures the correct representation of bio-energy feedstock yield from the watershed.

Feedstock Yields

The calibrated and validated SWAT model was used to simulate the potential feedstock yield of six bio-energy crops from the pastureland and croplands (1,669 km^2) of the UPRW. The model-simulated feedstock yields were compared for the two dominant Mississippi soils (MS048, and MS089) in the watershed. The MS048 and MS089 soils covered about 28.35% of the pastureland and cropland area in the watershed. The soil characteristics of MS048 soil include: fine sandy loam; distributed in the higher slope areas (8-12%); well drained soil with percentage fraction of clay 8.5%, silt 26.89%, and sand 64.61%; erodibility factor of 0.28; and bulk density of 1.45 g/cm3. Similarly the soil characteristics of MS089 soil include: silt loam; distributed in lower slope areas (0-8%); somewhat poorly drained soil with a percentage fraction of clay 22.5%, silt 52.72%, and sand 24.78%; erodibility factor of 0.32; bulk density of 1.39 g/cm3.

In an average feedstock yield, the MS048 soils had a 14% greater yield than the MS089 soils. In an analysis of 28 years of average annual watershed feedstock yield results, it was found that Miscanthus grass was the greatest feedstock yield from both MS048 and MS089 soils followed by Alfalfa, Switchgrass, Johnsongrass, Soybean, and Corn. Based on the model simulated feedstock yield results from two different soils (Table 3), it was estimated that the pastureland and cropland of the UPRW (1,669 km2) can produce 373,849 Mg of average feedstock annually if Miscanthus grass is grown in the watershed (Fig. 2). Similarly Alfalfa, Switchgrass, Johnsongrass, Soybean, and Corn can produce average annual feedstock of 206,077 Mg; 132,004 Mg; 47,576 Mg; 37,814 Mg; and 22,069 Mg respectively (Fig. 2) from the UPRW.

Table 3. Annual average sediment yield and watershed feedstock yield for bio-energy crops

Bio-energy	Area (km^2)		Sediment yield (Mg/ha		Crop yield (Mg/ha		Watershed feed-
Crops	MS048	MS089	MS048	MS089	MS048	MS089	stock yield (Mg)
Miscanthus	188	181	1.62	0.68	11.29	8.93	373,849
Alfalfa	188	181	4.80	1.58	5.42	5.76	206,077
Switchgrass	188	181	3.09	1.03	3.88	3.26	132,004
Johnsongrass	188	181	6.51	2.89	1.33	1.25	47,576
Soybean	188	181	14.19	6.11	1.07	0.98	37,814
Corn	188	181	16.90	7.00	0.63	0.57	22,069

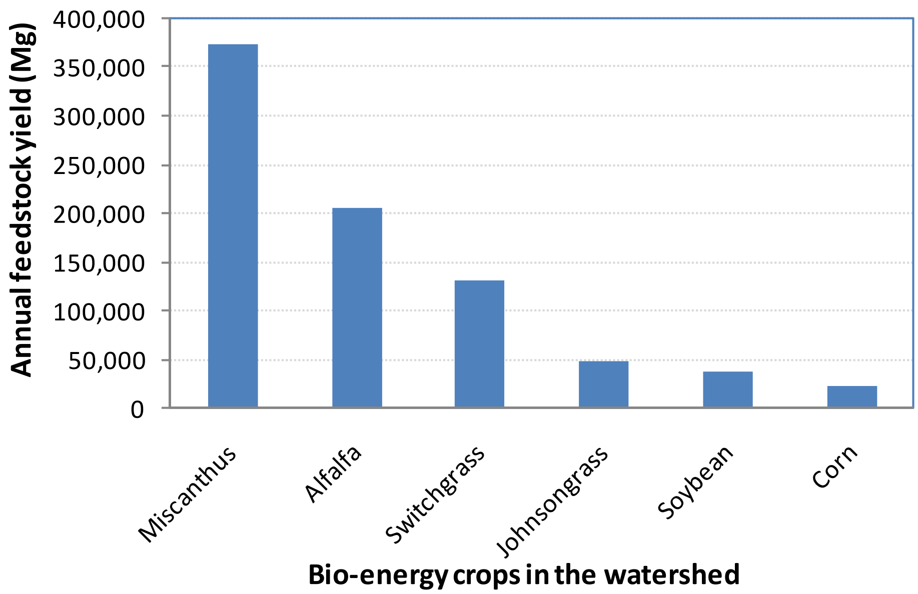

Figure 2. Model predicted long-term (28 years) average annual feedstock yield (Mg) for six bio-energy crops in the watershed.

Water Quality

Model simulated results determined that the corn crop scenario in the watershed had the greatest annual average sediment yield (12.04 Mg/ha) and the Miscanthus grass scenario had the least (1.16 Mg/ha) sediment yield (Table 4). The SWAT model simulation determined that the average annual water yield differed up to 5% from soybean and alfalfa bio-energy crops scenarios in the watershed. The model-estimated simulation results showed that the alfalfa crop had the greatest (519 mm) evapotranspiration demand, and the soybean crop had the least (485.65 mm; Table 4).

Table 4. Annual ET demand, water yield, and sediment yield for bio-energy crops

Bio-energy crops	ET demand (mm)	Water yield (mm)	Sediment yield (Mg/ha)
Miscanthus	506.89	614.21	1.16
Alfalfa	519.00	602.27	3.22
Switchgrass	511.59	609.66	2.08
Johnsongrass	505.06	616.21	4.73
Soybean	485.65	635.49	10.23
Corn	511.98	609.27	12.04

ET = evapotranspiration

Conclusion

The overall results of this study determined that long-term average annual feedstock yield from the UPRW was found the greatest when growing Miscanthus grass followed by Alfalfa, Switchgrass, Johnsongrass, Soybean, and Corn. Model-simulated results determined that Miscanthus grass can produce 373,849 Mg of feedstock annually, followed by Alfalfa (206,077 Mg); Switchgrass (132,077 Mg); Johnsongrass (47,576 Mg); Soybean (37,814 Mg); and Corn (22,069 Mg), respectively. Miscanthus grass demonstrated the greatest potential feedstock yield (81% greater than Alfalfa) in this study. Model-simulated results determined that the corn crop scenario in the watershed had the greatest annual average sediment yield (12.04 Mg/ha), and the Miscanthus grass scenario had the least (1.16 Mg/ha) sediment yield. The SWAT model-simulated results suggested that growing Miscanthus grass in the UPRW would have the greatest feedstock source and water quality benefits.

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