Biomass and Bioenergy 83 (2015) 50–59

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Research paper

Water quantity implications of regional-scale switchgrass production in the southeastern U.S.

Sheila F. Christopher [a,*], Stephen H. Schoenholtz [a], Jami E. Nettles [b]

[a] Virginia Water Resources Research Center, Virginia Tech, Blacksburg, VA 24061, USA
[b] Southern Timberlands Research, Weyerhaeuser Co., Columbus, MS, USA

A R T I C L E I N F O

Article history:
Received 27 November 2014
Received in revised form
15 July 2015
Accepted 7 August 2015
Available online 10 September 2015

Keywords:
Switchgrass
Loblolly pine plantation
Stream flow
SWAT
Land-use change
Southeastern U.S.

A B S T R A C T

Expansion of ethanol production has led to regional-scale cultivation of cellulosic biofuel crops, such as switchgrass (*Panicum virgatum* L.), on agriculturally marginal lands. A range of forest-based solutions are also being evaluated, especially in the southeastern U.S. However, there may be unanticipated environmental consequences, including changes in water export when managing forests to accommodate biofuel demands at a regional scale. We used the Soil Water Assessment Tool (SWAT) to simulate effects of regional-scale conversion of loblolly pine (*Pinus taeda* L.) plantations to switchgrass biofuel production on stream flow in the ~5 million ha Tombigbee River Watershed in the southeastern U.S. Greater than 50% of the Tombigbee Watershed is forested, with 20% of the watershed supporting primarily loblolly pine forests. We modified the SWAT model by adding five age classes of loblolly pine trees, to more accurately represent existing forested systems. We found that maximum conversion of loblolly pine to switchgrass, affecting 7% of the watershed, represented an extreme land-use change and resulted in a 4% increase in annual stream flow. The more operationally and economically feasible option of converting young (≤4 yrs) and old (≥16 yrs) loblolly pine stands to switchgrass on <8% slope (2% of the watershed) resulted in a 2% increase in stream flow. Changes in annual stream flow were driven primarily by alterations in evapotranspiration (ET). Seasonal changes in stream flow were attributed to complex interactions among water-balance components of ET, surface flow, and groundwater flow.

1. Introduction

Fluctuations in oil prices and strong interest in achieving energy independence have led to a dramatic expansion in ethanol production and alteration of the agricultural landscape [1,2]. Currently, in the U.S., ethanol biofuel production is predominately from the fermented sugars in corn (*Zea mays* L.); of the approximately 50.3 billion liters of ethanol produced in the U.S. in 2012, >95% came from corn starch [3]. However, competition of feed and food demands on grain supplies will eventually limit expansion of corn ethanol capacity [4,5]. Energy production from cellulose-based biomass (such as corn stalks and wheat straw, native grasses, trees, and forest residues), rather than from sugar-based materials, can provide an alternative non-food, non-feed-based feedstock [3]. Early studies indicate warm-season C4 perennial grasses such as switchgrass (*Panicum virgatum* L.) retain soil and nutrients in place, require lower fertilizer inputs, and are efficient water users, thus reducing water quality and quantity impacts often associated with corn production [6–11].

Demand for dedicated energy crops is expected to grow with development of bioenergy markets [12], resulting in significant alterations to current land-use [13]. Large-scale cultivation of cellulosic biofuel crops, such as switchgrass, on agriculturally marginal land or surplus lands using standard agricultural practices is one option being considered to meet biofuel demand [14]. Intensively managed forested lands could also be converted to agro-forestry systems for biofuel production [15]. Production of switchgrass from forested systems could diversify economic returns for land-owners while maintaining soil quality and biodiversity without significant diversion of agricultural crops from food production [16].

The southeastern and Gulf Coast regions of the U.S. have >15 million ha of pine (*Pinus* spp.) plantations [17] and some of the most

* Corresponding author. Present address: University of Notre Dame, Environmental Change Initiative, 1400 East Angela Blvd, South Bend, IN 46617, USA.
E-mail addresses: sheila.christopher@nd.edu (S.F. Christopher), stephen.schoenholtz@vt.edu (S.H. Schoenholtz), jami.nettles@weyerhaeuser.com (J.E. Nettles).

http://dx.doi.org/10.1016/j.biombioe.2015.08.012
0961-9534/

rapid population growth in the country, along with increasing pressure to develop these forested lands [17,18] to accommodate cellulosic biofuel demands [19]. This region of the U.S. could be a vital source of cellulosic biofuel because of its long growing season, favorable temperature, sufficient water, and suitable soil [20]. However, expansion of biofuel production may cause unintended environmental consequences that are not yet understood [13,21–24], especially at large regional scales [25–27].

One of the primary concerns with switchgrass is its potential to increase water export from watersheds [28,29]. The few studies that have looked at conversion of pine forests to grasslands observed higher annual stream flow (e.g., [30,31]), attributed to reductions in evapotranspiration (ET) and interception by vegetation, increased storm flow, and increased baseflow via increased groundwater recharge [30–32]. To date, there are no reports directly assessing impacts on stream flow of large-scale switchgrass production replacing pine forests. Given the expected differences in stream flow from pine forests versus switchgrass plantations, it is important to consider potential changes in regional water output that are likely to occur if hundreds of thousands of hectares of land are converted to switchgrass production, especially given the potential for associated environmental responses such as water-quality degradation that are often integrally linked with stream flow changes [25,26,28].

Field experiments using paired watersheds are commonly used to assess effects of changes in land use on stream flow, but are limited to smaller basins where applying land-use treatments on a watershed scale are possible. In single-watershed experiments, effect of land-use change on water resources is assessed by measuring conditions before and after the change in land use. In these experiments, it is more difficult to separate effect of land-use change from effects of changes in weather and climate patterns. Regional field-scale measurements to examine large-scale effects of vegetation land-use change on water resources are cost-prohibitive and, in most cases, it is also difficult to control experimental boundary conditions and to measure precipitation and stream flow accurately at these larger spatial scales.

In recent years watershed-scale hydrologic models have frequently been used to simulate effects of land-use change and management scenarios at a range of spatial scales [25,26,33–37]. The Soil and Water Assessment Tool (SWAT) can model effect of regional-scale switchgrass production on water resources, but has several limitations that make it difficult to apply to land-use change involving forests, as SWAT assumes all trees on the landscape are even-aged and mature.

To examine potential effects of large-scale conversion of forests for biomass production of a perennial herbaceous crop, we evaluated regional-scale impacts to stream flow of converting existing pine forests to a switchgrass bioenergy cropping system under a gradient of conversion scenarios. In a unique collaboration with Weyerhaeuser Company, who are assessing potential impacts of large-scale conversion of loblolly pine (*Pinus taeda* L.) forests to biofuel production in the southeastern U.S., we modified the SWAT model by inserting loblolly pine stands of varying age classes in the five-million-ha Tombigbee Watershed of the southeastern U.S. (Fig. 1), where large-scale commercial loblolly pine plantations currently exist and where switchgrass production is feasible.

We used the model to predict effects on stream flow of three land-use-change scenarios recommended by Weyerhaeuser, ranging from maximum conversion of pine plantations to switchgrass to a more operationally and economically realistic and modest conversion of pine plantations to switchgrass. We predicted that changes in seasonal and annual stream flow, compared to the baseline model using existing land-use categories, would be highest with the maximum conversion and least with more conservative conversion invoking more operational limitations. We hypothesized that changes in stream flow among the conversion scenarios would be controlled primarily by differences in the ET component of the water balance equation for the Tombigbee Watershed in Alabama and Mississippi, U.S.

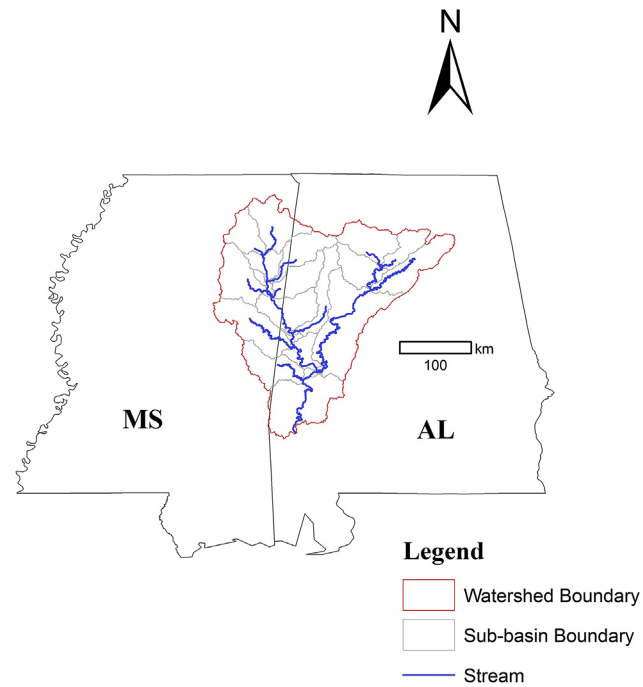

Fig. 1. The Tombigbee Watershed encompasses approximately five million ha and is a major subwatershed of the Mobile River Basin, draining portions of Mississippi (MS) and Alabama (AL), U.S. Approximately 53% of the watershed is forested, 23% is agricultural, 6% is urban, and 12% contains other land-use categories.

2. Materials and methods

2.1. Study watershed

The Tombigbee Watershed encompasses approximately five million ha and is a major subwatershed of the Mobile River Basin, draining portions of Mississippi and Alabama (Fig. 1). Cities within the Tombigbee Watershed with populations of $\geq$100,000 include Birmingham and Tuscaloosa, Alabama. Approximately 53% of the watershed is forested, 23% is agricultural, 6% is urban, and 12% contains other land-use categories. Rural land-use activities include row crops such as cotton, corn, and soybeans; aquaculture; poultry and cattle production; and silviculture. Major industries in the basin include power production; and chemical, pulp, paper, iron, steel, coal, and textile production [38].

The major physiographic province in the Tombigbee Watershed is Coastal Plain with some Piedmont and Valley and Ridge physiographic provinces located in the northeastern corner of the watershed [38]. Piedmont is generally characterized by igneous and metamorphic rocks, whereas Valley and Ridge consists of a series of parallel ridges and valleys, all having a northeast orientation and underlain by sandstone, shale, limestone, and dolomite rocks. The Coastal Plain is primarily underlain by unconsolidated or poorly consolidated sands, gravels, clays, and limestone. Elevation in the study unit ranges from 76 to 231 m and mean annual precipitation is 1397 mm (2001–2008) [38]. Mean annual stream flow of the Tombigbee River Basin is 866 m^3/s (2001–2008) [39]. The principal tributary to the Tombigbee River is the Black Warrior River Basin

(1.6 million ha), which has a mean annual stream flow of 278 m^3/s and is about 32% of the mean annual stream flow from the Tombigbee River Basin [38].

2.2. The Soil and Water Assessment Tool (SWAT) set-up and parameterization

We calibrated and validated a baseline SWAT model [40] in the Tombigbee Watershed to evaluate effects of regional-scale cellulosic biofuel conversion scenarios on stream flow. We compiled the baseline SWAT model for the Tombigbee Watershed using ArcSWAT version 2009.93.7b. This allowed derivation of model parameters from readily-available geographic data within ArcGIS geographic information system (GIS) software (Table 1). A summary of all input data is listed in Table 1. We obtained topography data from the National Elevation Dataset (NED) 30 m Digital Elevation Model (DEM) [41] to delineate stream channels and sub-basins. We obtained daily maximum temperature (°C), minimum temperature (°C), and precipitation (mm) from the National Climatic Data Center [42]. We used 19 climate stations with daily temperature and precipitation data for model calibration (2001–2008) and validation (1994–2000). We obtained soil data from the United States Department of Agriculture (USDA) Natural Resource Conservation Service [43] State Soil Geographic Database (STATSGO). The STATSGO data have a scale of 1:250,000, are designed to be used for large basin modeling, and have been shown to be adequate for modeling large watersheds [44]. The Tombigbee Watershed has 131 different soil types, 71 in Alabama and 60 in Mississippi, based on the STATSGO database.

2.3. Modification of loblolly pine data for SWAT

We modified the loblolly pine land cover data in SWAT because the SWAT model assumes all trees are even-aged and mature. We obtained land-cover data from the National Land Cover Dataset [45]. Using Hawth's Tools Random Selection Sampling Module for ARCGIS 9.3.1 [46], we first divided pine land cover in the Tombigbee Watershed into ~five equal and randomly selected parts. We then assigned one age class to each part representing tree ages of 1, 4, 8, 12, and 16 years for loblolly pine.

In the SWAT management input files, for each of the five age classes, we assigned parameter values based on either data from the literature or modeled data (Table 2). We obtained initial January leaf area index (LAI_INT) for each age class (Fig. 2, Table 2) using a model described in Rojas et al., 2005 [47]. Because our model started in January 1 of each year, this required that each pine age class was assigned a winter LAI value. Briefly, this model was developed using 86 forest nutrition studies across 10 states in loblolly pine plantations, where leaf area index (LAI) is described as:

$$\mathrm{LAI} = \mathrm{VG}/\mathrm{GE} \tag{1}$$

where VG is stemwood biomass and GE is a growth efficiency parameter (slope). In an attempt to describe variation found across sites, we allowed the GE parameter to vary as a function of edaphic, stand, foliar, and climate variables. We obtained VG using a forest growth and yield model (Nettles, Unpublished data) using typical silvicultural conditions for a southern loblolly pine plantation with a site index_{25} of 21 m, thinning after canopy closure (when trees were 10 years old), and fertilization twice during the 30-yr rotation with 135 kg ha^{-1} N + 13 kg ha^{-1} P. Thinning is a silvicultural practice that decreases stand density to allocate site resources to remaining crop trees [48].

Potential heat units (PHU) are an estimate of the thermal timeframe of the growing season, i.e., the energy needed to support a plant from budding to leaf senescence. In SWAT, once vegetation reaches total growth in a growing season in the model, the LAI for the vegetation is set to zero and the vegetation no longer intercepts rainwater, takes up water from the soil, or evapotranspires. Because evergreen loblolly pine does not stop transpiring or intercepting rainwater, we utilized the method of von Stackelberg [49] and we extended the active season by assigning PHU a value of 3,500, more than twice the default value of 1432.5, representing the highest allowable value for this parameter in the model.

We obtained total biomass (kg ha^{-1}-the sum of leaf, stem, branch, fine-root and coarse-root biomass) values for loblolly pine using a loblolly pine forest growth and yield model, FASTLOB [50]. Because this forest growth and yield model did not include tree age <6 yr, a simple regression model was created that predicted total tree biomass (y) from stem biomass (VG) to accommodate all pine ages:

$$y = 1.411\mathrm{VG} + 7756.6,\ R^2 = 0.99,\ (p < 0.0001) \tag{2}$$

where pine stemwood biomass (VG) was obtained as mentioned above. Predicted total biomass (y) from Equation (2) for each age class (BIO_INIT) was then used in the SWAT model (Table 2, Fig. 3).

2.4. Model calibration and validation implementation

We conducted a sensitivity analysis to identify the most influential parameters affecting modeled stream flow to avoid over-parameterization [51] and to determine parameters for successful model calibration [52]. We performed the sensitivity analysis using the ArcSWAT interface for the period of 2004–2006, representing a wet year in 2004, a medium year in 2005, and a drier year in 2006 (mean annual precipitation was 1649 mm, 1463 mm, and 1310 mm, respectively).

We calibrated and validated the baseline model on a monthly time step by comparing modeled versus measured stream flow at

Table 1
Summary of input datasets for the SWAT model used for the Tombigbee Watershed.

Data type	Dataset	Source
Geospatial data layer	DEM-30 m	USGS[a]
	Soils	STATSGO[b]—USDA-NRCS[c]
	Land cover	NLCD[d] 2001—USGS
Climate data	Precipitation and temperature-19 climate stations	NCDC[e]
Measured data	Stream flow, at Coffeeville, AL	USGS gauging station 02469761

[a] United State Geological Survey.
[b] State Soil Geographic Database.
[c] United State Department of Agriculture-Natural Resources Conservation Service.
[d] National Land Cover Dataset.
[e] National Climate Data Center.

Table 2
Parameters used in the SWAT model for each pine age-class in the Tombigbee Watershed.

Parameter[a]	Age-class (years)					Data source
	1	4	8	12	16	
LAI_INIT (January)	0.01	0.22	1.34	0.79	1.34	Fig. 2
BIO_INIT (Kg/ha)	8278	10,587	42,559	51,844	99,111	Fig. 3
PHU_PLT	3500	3500	3500	3500	3500	[48]
CHTMX (m)	30	30	30	30	30	[81,82]
BLAI	5	5	5	5	5	[83]
ALAI	0.01	0.22	1.34	0.79	1.34	Fig. 2
Mat years	30	30	30	30	30	[81]
RDMX (m)	5	5	5	5	5	[84]
CURYR_Mat (yr)	1	4	8	12	16	Age at start of the model

[a] LAI_Int = Initial leaf area index, BIO_Int = Initial dry weight biomass, PHU_PLT = Total number of heat units or growing degree days to bring the plant to maturity, CHTMX = Maximum height, BLAI = Maximum potential leaf area index, ALAI = Minimum leaf area index for planting during dormant period, Mat Years = Number of years for tree to reach full development, RDMX = Maximum rooting depth, and CURYR_Mat = Current age of tree.

the outlet of the Tombigbee Watershed during a calibration period (2001–2008) and validation period (1994–2000), with the first two years as a "warm-up" period [53]. "Warm-up" ensured reasonable starting values for model variables after model initialization and is common for hydrologic models. We obtained observed stream flow data from the USGS gauging station 02469761 on the Tombigbee River, at Coffeeville, AL (Alabama Hydrologic Unit Code 03160203). We used a public-domain program (SWAT-CUP 3.1.3), which links the SUFI-2 (Sequential Uncertainty Fitting, version 2) procedure to SWAT for calibration and validation. We calculated the goodness-of-fit for both calibration and validation periods using linear regression and the Nash-Sutcliffe Efficiency (NSE) coefficient [54]. The NSE can range from $-\infty$ to 1 with a negative value indicating that the mean of observed values is a better predictor then the model and generally indicates an unacceptable performance. Values > zero are often considered acceptable and values ≥ 0.5 are considered to be good-to-excellent model performance for stream flow [52].

2.5. Land-use scenarios

We calibrated a baseline model based on existing land-cover conditions and simulated three land-use-change scenarios using the calibrated SWAT model to evaluate hydrologic effects of regional-scale loblolly pine land-use conversion to switchgrass biofuel production within the Tombigbee Watershed. This study was conducted in conjunction with ongoing research of Weyerhaeuser Company, who studied operational methods and sustainability of growing switchgrass in a forested setting; scenarios were based on actual operational methods for growing switchgrass in Mississippi and Alabama [19,55–57].

2.5.1. Baseline model

The calibrated model represented current baseline conditions where we simulated current land cover and management practices that are common in managed loblolly pine forests in Mississippi and Alabama. We allocated ~20% of the pine land use in each subwatershed to streamside management zones (SMZs – silvicultural buffer zones with restricted forest management activity to protect stream habitat condition and water quality) based on Weyerhaeuser ownership patterns in Mississippi and Alabama. The other 80% of the pine land use in each subwatershed was allocated as managed loblolly pine plantation (with five age classes present). We placed the oldest loblolly pine tree class (i.e., age $\geq$ 16 years) in the SMZs to represent mature pine, based on current forestry best management practices [58].

2.5.2. Scenario 1 (maximum conversion)

All pine land-cover on <15% slope was converted to switchgrass. We chose a threshold of 15% as an upper limit for unacceptable erosion and operability based on experience and visual examination of operational tracts [59]. This scenario represents an extreme case – maximum operational conversion of loblolly pine of all age

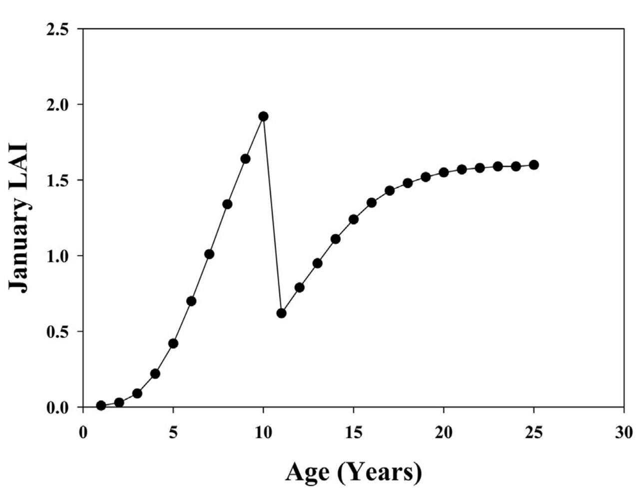

Fig. 2. January leaf area index (LAI) values for loblolly pine used in the SWAT model at ages 1, 4, 8, 12, and 16 years. The decrease in LAI in Year 10 coincides with a stand thinning. Because our model started on January 1 of each year, this required that each pine age class was assigned a winter LAI value.

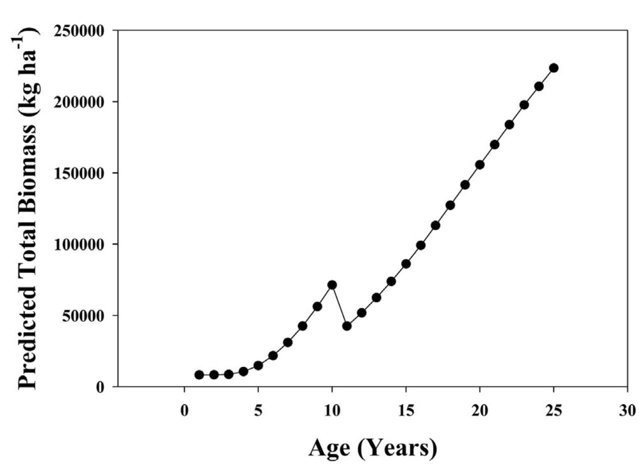

Fig. 3. Predicted total biomass values for loblolly pine used in the SWAT model at age 1, 4, 8, 12, and 16 years. The decrease in LAI in Year 10 coincides with a stand thinning.

classes to switchgrass, including very young pine, almost mature pine, and those in between (mid-rotation pine). Conversion could occur in the pine that was close to the beginning (very young) or close to the end (almost mature) of the typical rotation. However, harvesting mid-rotation pine trees for sawtimber under this scenario would be economically infeasible. Mid-rotation pine trees have considerable investment in time and management resources (e.g., fertilization and thinning) that could not be monetized and investment would be lost if harvested before it could be sold for sawtimber. We retained SMZs (primary buffer) in this model. In addition to the primary SMZs prescribed by silvicultural BMPs, in the bioenergy scenarios, secondary SMZs were allocated. These secondary SMZs were based on a survey of operational-scale intercropped tracts in Mississippi and Alabama [59] that found switchgrass planting contractors left an additional unplanted buffer approximately equal to the primary silvicultural SMZ (~20%) to protect water resources during biofuel establishment. We assigned an even distribution of the five loblolly pine age classes to the secondary, bioenergy buffers.

2.5.3. Scenario 2 (young and old pine converted, <15% slope)

We converted youngest (≤4 year) and oldest (≥16 years) loblolly pine age classes to switchgrass on <15% slope. This scenario represented a more realistic economic situation, where conversion would only occur after standing mature pine was harvested or where pine stands were very young. For this scenario, we also retained 20% primary and 20% secondary riparian buffers as described above.

2.5.4. Scenario 3 (young and old pine, <8% slope)

We converted youngest (≤4 year) and oldest (≥16 years) loblolly pine age classes on <8% slope to switchgrass. This represented the most feasible economic scenario and more operationally realistic slopes. We also retained primary and secondary riparian buffers as described above.

We used the default parameters for Alamo variety of switchgrass in our simulations with a few modifications. Switchgrass was planted as a mature stand with an initial biomass of 500 kg ha^{-1}, winter LAI of 0.01, and 2.2 m rooting depth. Each year, we assumed switchgrass required 1432 PHU to reach maturity. Growth parameters included radiation-use efficiency of 47 kg MJ^{-1}, base temperature of 12 °C, and an optimal temperature of 25 °C [60]. We simulated growth by increasing LAI over the growing season from the initial value of 0.01 to a maximum value, BLAI, of 5.0, followed by decrease to senescence. To allow crop drying, we delayed harvesting until reaching 120% of heat units required to reach maturity (which occurred in August) and harvested 80% of above-ground biomass each year.

2.6. Water balance

We examined SWAT water-balance components to determine what components of the water balance controlled changes in stream flow in response to the three biofuel management scenarios described above. Observed stream flow changes associated with land-use change can be evaluated by considering the water balance over long enough time periods whereby net changes in storage approximate zero and can be defined as:

$$Q = P - ET - DA \pm \Delta S \quad (4)$$

where Q is stream flow, P is precipitation, ET is evapotranspiration, DA is percolation to the deep aquifer, and ΔS is change in storage (assumed to be zero).

Assuming no long-term change in P, and because Q is composed of ground water flow in the shallow aquifer, lateral shallow subsurface flow, and overland surface runoff, increasing Q in the watershed would be a result of increasing groundwater flow, lateral flow, and/or surface runoff, or decreasing ET. Decreasing Q in the watershed would be from decreasing flow components (groundwater flow, lateral flow, and/or surface runoff) or increasing ET.

3. Results and discussion

3.1. Calibration and validation

We selected four parameters for calibration based on the sensitivity analysis (Table 3). Monthly stream flow was most sensitive (with a rank of 1) to Manning's N (CH_N2), the channel roughness coefficient. Channel effective hydraulic conductivity (CH_K2), which characterizes the relationship between stream hydrology and the groundwater system, dictating whether a stream is losing or gaining volume from groundwater, was ranked second most-sensitive. The curve number (CN2) was ranked third most-sensitive, and threshold water table depth in the shallow aquifer for return flow (GWQMN) was ranked fourth most-sensitive. Groundwater flow returned to the stream is allowed by SWAT only if the depth in the shallow aquifer ≥ GWQMN.

Comparison between observed and modeled monthly flow showed generally good agreement, both during baseflow and high flows (Fig. 4). Analysis of calibration and validation periods indicated more than adequate prediction capabilities of the model with NSE values for stream flow at 0.83 and 0.91 for the calibration and validation, respectively. These values are considered indicative of good model performance for stream flow [52]. Regression results were also satisfactory, with R^2 of 0.90 ($p < 0.0001$) and 0.93 ($p < 0.0001$), for calibration and validation, respectively.

3.2. Land-use scenario results

Converting maximum possible loblolly pine to switchgrass (Scenario 1) in areas of <15% slope resulted in conversion of 349,727 ha or 7% of the Tombigbee Watershed. Converting young (≤4 yr) and old (≥16 yr) loblolly pine age classes to switchgrass on <15% slope (Scenario 2) resulted in 163,900 ha or 3% of the watershed converted to switchgrass, whereas converting young and old loblolly pine age classes to switchgrass on <8% slope (Scenario 3) resulted in 108,097 ha or 2% of the watershed in switchgrass (Table 4).

On an annual basis, large-scale conversion of loblolly pine to

Table 3
SWAT parameters selected for calibration based on sensitivity analysis and final calibrated value or range.

Parameter code	Parameter description	Sensitivity rank	Value or range
CH_N2[a]	Mannings "n" for the main channel	1	0.054
CH_K2[a] (mm/h)	Channel effective hydraulic conductivity	2	0.94
CN2	Curve number	3	52.3–87.4
GWQMN[a] (mm)	Threshold water table depth in the shallow aquifer for return flow	4	46.1

[a] Parameter chosen for calibrating across the entire watershed.

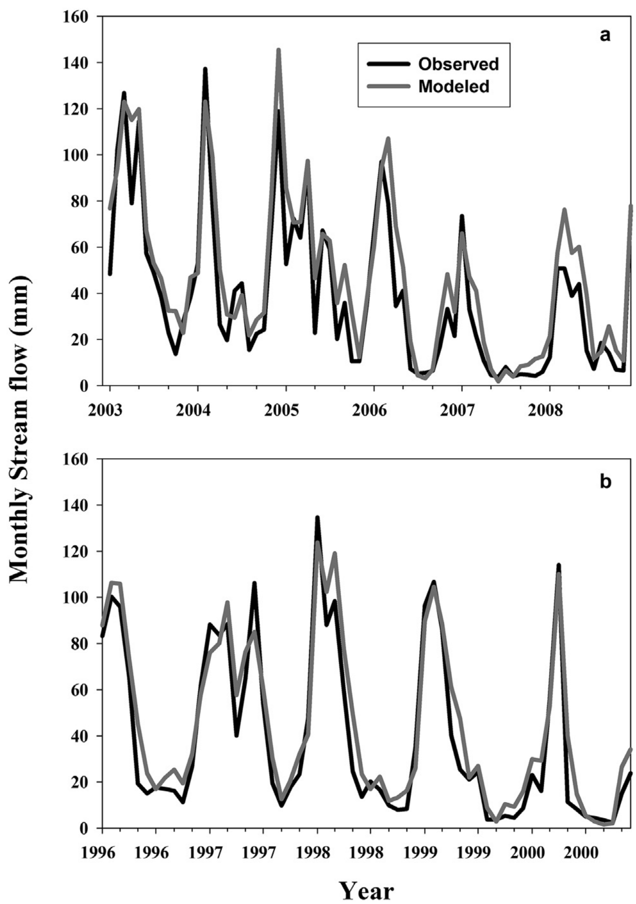

Fig. 4. Observed stream flow at the outlet of the Tombigbee Watershed versus modeled stream flow during the a. calibration period (2003–2008) b. validation period (1996–2000).

switchgrass resulted in higher stream flow in the Tombigbee Watershed under all three conversion scenarios when compared to existing baseline condition. Mean annual stream flow increases ranged from 3.0% (17 mm) to 7.7% (23 mm) from 2003 to 2008 when converting all possible loblolly pine on slopes <15% to switchgrass (Scenario 1) with a mean annual 4.2% (21.0 ± SE 0.9 mm) increase during the six-year study period (Table 4). Conversion of young and old pine to switchgrass resulted in a mean annual increase of 2.3% (13 ± SE 1.2 mm) and 1.9% (10 ± SE 1.2 mm) for Scenario 2 (<15% slopes) and Scenario 3 (<8% slopes), respectively.

Conversion of young and old loblolly pine age classes (Scenarios 2 and 3) to switchgrass also generally resulted in increased mean monthly stream flow (Fig. 5). Mean monthly increases in stream flow ranged from 1 − 5% in the <15% slope conversion (Scenario 2) and 1–4% in the <8% slope conversion (Scenario 3). Maximum conversion of all pine age classes on <15% slopes to switchgrass via Scenario 1 resulted in a 1–9% increase in stream discharge during all times of the year except summer (Fig. 5). In contrast, during summer months, mean stream flow was 1% lower in June and 2% lower in July in the Scenario 1 model with maximum conversion to switchgrass than in the baseline model with no conversion to switchgrass.

3.3. Water balance and land-use change

3.3.1. Mean annual stream flow

For annual water balance components, the most notable difference among the scenarios was in mean annual ET (Fig. 6), which decreased 3% (23 mm), 2% (14 mm), and 1% (11 mm) relative to the baseline model for Scenario 1, 2, and 3, respectively. Evapotranspiration is a major component of the water balance in pine forests [61–66]. We suggest that this decrease in ET could explain most variability in stream flow among scenarios on an annual basis. These results support our hypothesis that the primary reason for the lower mean annual stream flow in the baseline model was caused by higher ET from trees compared to switchgrass. That is, higher ET from the baseline watershed that contained more pine stands resulted in lower mean annual stream flow than the scenarios where pine was converted to switchgrass. The most commonly used comparison of plant and grass water use, the Zhang curve [67], gives an estimate of annual stream flow based on a large global data set. Although the curve is based on a broad aggregation of data and makes other simplifying assumptions, estimates of ET change based on the Zhang curve for our three scenarios were similar to our SWAT-modeled values of ET change. At an average annual rainfall of 1400 mm, the curve shows the ET of grass to be 310 mm yr^{-1} lower than a pine forest, representing 22% of rainfall. Using this value, converting 7%, 3%, and 2% of the watershed from pine forest to grass would yield ET decreases of 22, 9, and 6 mm, respectively. Our model similarly predicted decreases of 23, 14, and 11 mm yr^{-1}, respectively.

Our results are consistent with other studies that suggest land-use change can have significant affect on annual stream flow, which is mainly driven by changes in ET [15,37,65,68,69]. In particular, a recent plot-scale study associated with the same experimental treatments in the North Carolina Coastal Plain found modeled mean annual ET rates of switchgrass to be 4–22% lower than loblolly pine ET [70]. Furthermore, our modeled mean annual values of ET for Alamo switchgrass were in agreement with other measured ET values for switchgrass in the southeastern U.S [47] and in the midwestern and northeastern U.S [71–75]. Finally, our results are consistent with other studies that have conversely converted perennial C4 grasslands (though not specifically switchgrass) to tree plantations and have shown lower stream flow associated with higher ET in tree plantations versus grasslands (e.g., [49,67,76,77]).

3.3.2. Mean monthly stream flow

We compared monthly water balance components between the two extreme models: the baseline model versus Scenario 1 (all possible pine on slopes <15% converted to switchgrass) to assess

Table 4
Change in Tombigbee Watershed land-cover and associated change in stream flow in the Tombigbee River for three model scenarios.

Scenario	Area of watershed converted (ha)	% Tombigbee land cover converted to switchgrass	% Mean annual stream flow increase
1. Maximum loblolly pine to switchgrass, <15% slope (Scenario 1)	349,727	7%	4.2 ± 0.8%
2. Youngest (≤4 yr) and oldest (≥16 yr) age classes of loblolly pine to switchgrass, <15% slope (Scenario 2)	163,900	3%	2.3 ± 0.2%
3. Youngest (≤4 yr) and oldest (≥16 yr) age classes of loblolly pine to switchgrass, <8% slope (Scenario 3)	108,097	2%	1.9 ± 0.1%

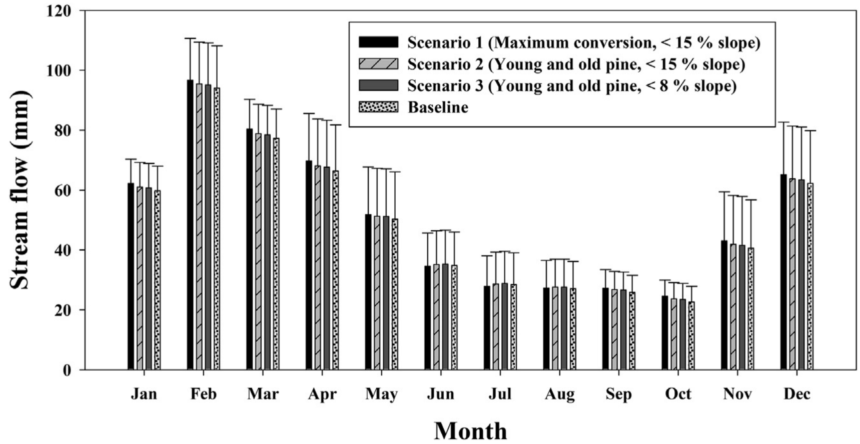

Fig. 5. Mean monthly stream flow (+SE) in the Tombigbee Watershed for the baseline model and the three scenarios: maximum conversion of loblolly pine to switchgrass on <15% slope (Scenario 1), conversion of young (≤4 yr) and old (≥16 yr) loblolly pine to switchgrass on <15% slope (Scenario 2), and conversion of young and old loblolly pine to switchgrass on <8% slope.

the most extreme changes in stream flow associated with conversion from loblolly pine forests to switchgrass biofuel production. In most months, Scenario 1 had lower mean monthly ET, yet higher mean monthly surface flow, lateral flow, and groundwater flow, which culminated in higher stream flow compared with the baseline model (where the landscape had considerably more pine trees) (Fig. 7). Mean monthly precipitation ranged between 86 and 162 mm, and mean monthly temperature was highest in July (27 °C) and lowest in December (7 °C); within-month variability for precipitation and temperature among the 19 climate stations in the Tombigbee Basin was very low. In May and June only, mean monthly ET was higher in the Maximum-conversion model (Scenario 1) versus the Baseline model, while surface runoff was concomitantly lower in the Scenario 1 model in May, June, and July (Fig. 7). Groundwater flow was lower only in July in the Scenario 1 versus the Baseline model, while stream flow was lower in Scenario 1 versus the Baseline model in June and July (Fig. 7).

Our results suggest that during the summer months, changes in stream flow in association with large conversion of pine forests to switchgrass was not only driven by changes in ET, but also by interaction among watershed components. Peak switchgrass LAI (~5) occurred in May and June, resulting in more ET in Scenario 1 versus the Baseline model. This higher ET in the Scenario 1 model resulted in concomitantly lower surface runoff but there was likely a lag time for higher ET to affect groundwater flow, a major component of the water balance (Fig. 6; 15) and thus a concomitant lower stream flow in Scenario 1 compared to the Baseline model did not occur until July, when the groundwater flow component was lower. We attribute differences in monthly water balance components to differences in ET among different degrees of pine-to-switchgrass conversion in our scenarios and resultant effect on soil storage, surface flow, subsurface flow, and stream flow rather than local differences in weather within the watershed because within-month variability in precipitation and temperature data was low during our study period (Fig. 7).

Our results are consistent with other studies that have suggested changes in vegetation result in a cascade of changes in the water balance components most noticeable on shorter rather than

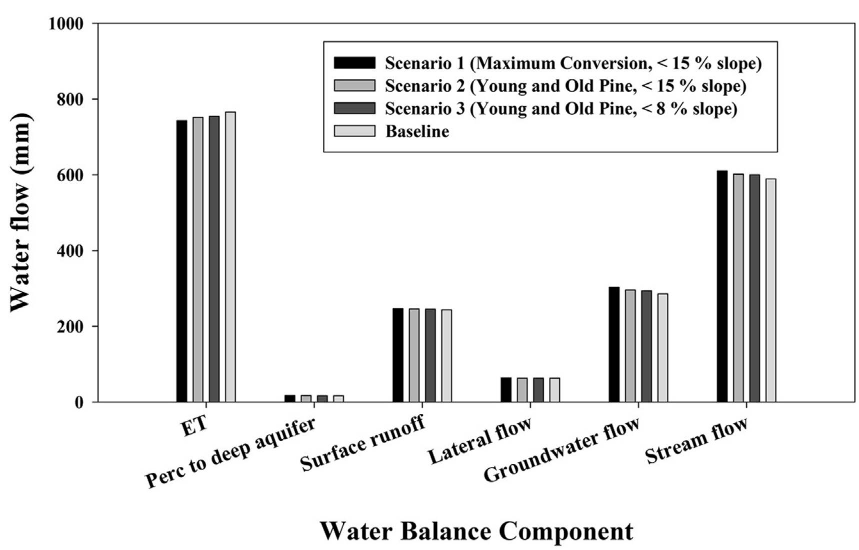

Fig. 6. Annual water balance components in the Tombigbee Watershed for the baseline model and the three scenarios: maximum conversion of loblolly pine to switchgrass on <15% slope (Scenario 1), conversion of young (<4 yr) and old (>16 yr) loblolly pine age classes to switchgrass on <15% slope (Scenario 2), and conversion of young and old loblolly pine age classes to switchgrass on <8% slope. (Mean annual precipitation is 1370 mm).

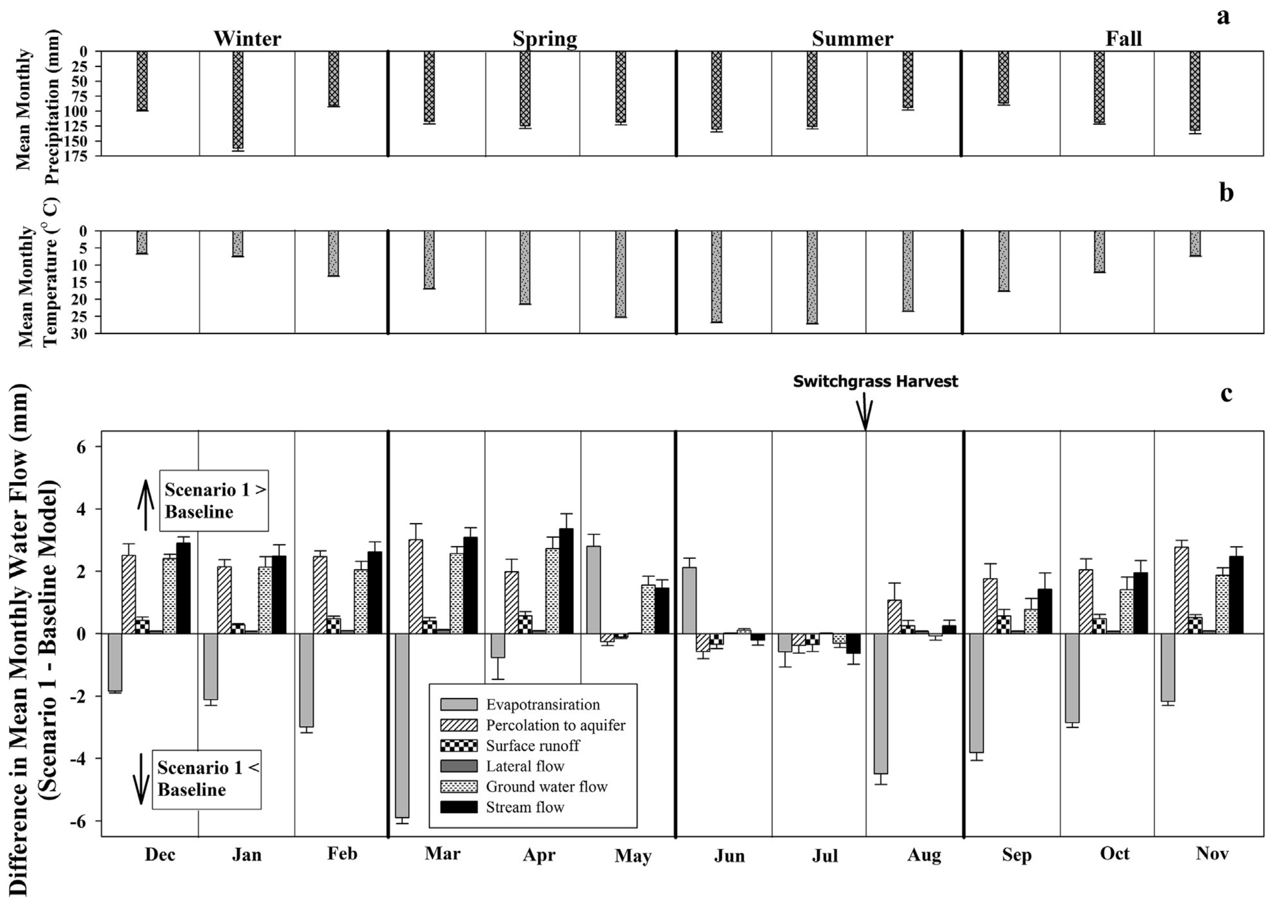

Fig. 7. Weather and water balance components in the Tombigbee Watershed showing a. mean monthly precipitation (+SE, 2003–2008), b. mean monthly temperature (+SE, 2003–2008), and c. difference in mean monthly water balance components (+1 SE) in the Tombigbee Watershed between Scenario 1 (maximum conversion of loblolly pine to switchgrass) minus the Baseline model (2003–2008). Positive values indicate a water balance component is greater in Scenario 1 than in the Baseline model; negative values indicate water balance component is less in Scenario 1 than in the Baseline model. Timing of simulated switchgrass harvest in August is indicated by an arrow.

annual time-scales [30–32,78–80]. The plot-scale study in North Carolina found higher transpiration rates in switchgrass (maximum daily rate of 2.1–2.3 mm) versus loblolly pine plots (maximum daily rate of 1.4–2.3 mm) during summer only, as we did in our model [70]. Others have suggested that seasonal stream flow dynamics are not solely affected by changes in ET, but also by certain seasonal factors, such as changes in soil moisture and resultant changes in surface and groundwater flow [15,31,70,81].

Most forest/grassland conversion studies report annual rather than monthly water balance components and stream flow [80]. Generalizing changes in stream flow in response to a change in a specific vegetation type (e.g., pine trees to switchgrass) is challenging because changes can vary considerably depending on the climate [79,80]. However, according to a review of 166 paired-watershed studies, effects of vegetation change on *seasonal* stream flow can be as or more important than impact on annual stream flow [80] because short-term changes in seasonal export can lead to water quality, water supply, ecological, and/or economic problems [80]. Our study highlights potential impacts of vegetation change on both annual and seasonal stream flow in the south-eastern U.S. and the need for more field research in various climates that would inform regional-scale hydrologic models. There is a specific need to not only measure ET dynamics associated with vegetation change over the entire year, but to also measure associated soil moisture, surface flow, groundwater flow, and stream flow [15].

4. Conclusions

We used a SWAT model for the Tombigbee Watershed to simulate effects of regional-scale conversion of loblolly pine plantations to switchgrass biofuel production on stream flow. Large-scale conversion of loblolly pine to switchgrass as modeled in Scenario 1 and affecting 7% of the 5 million-ha Tombigbee Watershed represents an extreme land-use change that is not economically rational. However, it does provide an extreme end-member indicating potential changes in regional stream flow if large-scale conversion of the current land use (in this case, pine forests) to a deciduous, non-irrigated perennial bioenergy crop such as switchgrass were to occur. The more operationally and economically feasible option of converting land currently supporting youngest and oldest stands of loblolly pine trees to switchgrass on <8% slope resulted in a 2% increase in annual stream flow. Changes in annual stream flow were driven by changes in ET. Seasonal changes in stream flow were more complex and were attributed to changes in ET and the subsequent responses of surface flow and groundwater flow contributing to stream flow. Further field and modeling studies are needed to advance our understanding of mechanisms of seasonal changes in hydrology related to regional-scale changes in vegetation and land-use.

Understanding regional-scale water quantity effects of cellulosic biofuel systems and developing effective management methods that mitigate environmental effects will be important to the ultimate success and sustainability of cellulosic biomass production strategies. These efforts will rely on hydrologic modeling for comparison of various management scenarios such as presented here.

Acknowledgments

This research was supported by Weyerhaeuser Company. Special thanks to Ralph Amateis and Julio Rojas for help with input model data.

References

[1] L. Paula, F. Birrer, Including public perspectives in industrial biotechnology and the biobased economy, J. Agric. Environ. Ethics 19 (3) (2006) 253–267.
[2] A.J. Ragauskas, C.K. Williams, B.H. Davidson, G. Britovsek, J. Cairney, C.A. Eckert, W.J. Fredrick, J.P. Hallet, D.J. Leak, C.L. Liotta, J.R. Mielenz, R. Murphey, R. Templer, T. Tschaplinski, The path forward for biofuels and biomaterials, Science 311 (2006) 484–489.
[3] US CRS (US Congressional Research Service), Agriculture-based Biofuels: Overview and Emerging Issues (R41282; May 1, 2013), 2013 (Report by Randy Schnepf).
[4] S. Nonhebel, Renewable energy and food supply: will there be enough land? Renew. Sustain. Energy Rev. 9 (2005) 191–201.
[5] M.R. Schmer, K.P. Vogel, R.B. Mitchell, R.K. Perrin, Net energy of cellulosic ethanol from switchgrass, Proc. Natl. Acad. Sci. 105 (2008) 464–469.
[6] S.B. McLaughlin, M.E. Walsh, Evaluating environmental consequences of producing herbaceous crops for bioenergy, Biomass Bioenergy 14 (1998) 317–324.
[7] V.R. Tolbert, L.L. Wright, Environmental enhancement of US biomass crop technologies: research results to date, Biomass Bioenergy 15 (1998) 93–100.
[8] D.J. Parrish, J.M. Fike, The biology and agronomy of switchgrass for biofuels, Crit. Rev. Plant Sci. 24 (2005) 423–459.
[9] M.A. Scanlon, P.R. Adler, A.A. Boateng, M.D. Casler, G. Sarath, Swithgrass as a biofuels feedstock in the USA, Can. J. Plant Sci. 86 (2006) 1315–1325.
[10] K.C. Stone, P.G. Hunt, K.B. Cantrell, K.S. Ro, The potential impacts of biomass feedstock production on water resource availability, Bioresour. Technol. 101 (2010) 2014–2025.
[11] L. Wright, A. Turhollow, Switchgrass selection as a “model” bioenergy crop: a history of the process, Biomass Bioenergy 34 (2010) 851–868.
[12] B.D. Solomon, J.R. Barnes, K.E. Halvorsen, Grain and cellulosic ethanol: history, economics, and energy policy, Biomass Bioenergy 31 (2007) 416–425.
[13] R.L. Rowe, N.R. Street, G. Taylor, Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK, Renew. Sustain. Energy Rev. 13 (1) (2009) 271–290.
[14] R. Lal, D. Pimentel, Biofuels from crop residues, Soil Tillage Res. 93 (2007) 237–238.
[15] W.H. Kim, D.M. Amatya, G.M. Chescheir, W.R. Skaggs, J.E. Nettles, Hydrologic effects of size and location of fields converted from drained pine forest to agricultural cropland, J. Hydraul. Eng. 18 (5) (2013) 552–566.
[16] S.B. McLaughlin, L. Adams Kszos, Development of switchgrass (*Panicum virgatum*) as a bioenergy feedstock in the United States, Biomass Bioenergy 28 (2005) 515–535.
[17] D.N. Wear, J.G. Greis, Southern Forest Resource Assessment (General Technical Report SRS-53), US Department of Agriculture Forest Service, Southern Research Station, Ashville, NC, 2002.
[18] J.A. Griffith, S.V. Stehman, T.R. Loveland, Landscape trends in Mid-Atlantic and Southeastern United States ecoregions, Environ. Manage. 32 (2003) 572–588.
[19] K.J. Minick, B.D. Strahm, T.R. Fox, E.B. Sucre, Z.H. Leggett, J.L. Zerpa, Switchgrass intercropping reduces soil inorganic nitrogen in a young loblolly pine plantation located in coastal North Carolina, For. Ecol. Manage. 319 (2014) 161–168.
[20] S.D. Wullschleger, E.B. Davis, M.E. Borsuk, C.A. Gunderson, L.R. Lynd, Biomass production in switchgrass across the United States: database description and determinants of yield, Agron. J. 102 (2010) 1158–1168.
[21] G. Berndes, Bioenergy and water — the implications of large-scale bioenergy production for water use and supply, Glob. Environ. Change 12 (2002) 253–271. Human Policy Dimensions.
[22] H.L. Welch, C.T. Green, R.A. Bebich, J.R.B. Barlow, M.B. Hicks, Unintended Consequences of Biofuels Production: the Effects of Large-scale Crop Conversion on Water Quality and Quantity, U.S. Geological Survey, Reston, VA, 2010.
[23] T.W. Simpson, A.N. Sharpley, R.W. Howarth, H.W. Paerl, K.R. Mankin, The new gold rush: fueling ethanol production while protecting water quality, J. Environ. Qual. 37 (2008) 318–324.
[24] P.R.D. Williams, D. Inman, A. Aden, G.A. Heath, Environmental and sustainability factors associated with next-generation biofuels in the US: what do we really know? Environ. Sci. Technol. 43 (2009) 4763–4775.
[25] Y. Wu, S. Liu, Impacts of biofuels production alternatives on water quantity and quality in the Iowa River Basin, Biomass Bioenergy 36 (2012a) 182–191.
[26] Y. Wu, S. Liu, Z. Li, Identifying potential areas for biofuel production and evaluating the environmental effects: a case study of the James River Basin in the Midwestern United States, Glob. Change Biol. Bioenergy 4 (2012b) 875–888.
[27] A. VanLoocke, C.J. Bernacchi, T.E. Twines, The impacts of Miscanthus x giganteus production on the Midwest US hydrologic cycle, Glob. Change Biol. Bioenergy 2 (2010) 180–191.
[28] N.N. Rabalais, R.E. Turner, D. Scavia, Beyond science policy: Gulf of Mexico hypoxia and the Mississippi River, BioScience 52 (2002) 129–142.
[29] National Research Council (NRC) of the National Academies, Water Implications of Biofuels Production in the United States, Committee on Water Implications of Biofuels Production in the United States, 2008.
[30] J.K. Ruprecht, N.J. Schofield, Analysis of streamflow generation following deforestation in southwest Western Australia, J. Hydrol. 105 (1989) 1–17.
[31] M.A. Bari, N. Smith, J.K. Ruprecht, B.W. Boyd, Changes in streamflow components following logging and regeneration in the southern forest of Western Australia, Hydrol. Process. 10 (1996) 447–461.
[32] Y.K. Zhang, K.E. Schilling, Increasing streamflow and baseflow in the Mississippi River since 1940s: effect of land use change, J. Hydrol. 324 (2006) 412–422.
[33] A.J.J. Van Rompaey, G. Govers, E. Van Hecke, K. Jakobs, The impacts of land use policy on the soil erosion risk: a case study in central Belgium, Agric. Ecosyst. Environ. 83 (2001) 83–94.
[34] A. Weber, N. Fohrer, D. Möller, Long-term changes of land use in a mesoscale watershed due to socio-economic factors—effects on landscape functions, Ecol. Model. 1/2 (2001) 125–140.
[35] N. Fohrer, D. Möller, N. Steiner, An interdisciplinary modelling approach to evaluate the effects of land use change, Phys. Chem. Earth 27 (9/10) (2002) 655–662.
[36] G. Sun, S.G. McNulty, J. Lu, D.M. Amatya, Y. Liang, R.K. Kolka, Regional annual water yield from forest lands and its response to potential deforestation across the southeastern United States, J. Hydrol. 308 (1–4) (2005) 258–268.
[37] K.E. Schilling, M.K. Jha, Y.K. Zhang, P.W. Gassman, C.F. Wolter, Impact of land use and land cover change on the water balance of a large agricultural watershed: historical effects and future directions, Water Resour. Res. 44 (2008) 1–12.
[38] J.B. Atkins, National Water-quality Assessment Program: Mobile River Basin, U.S. Geological Survey Fact Sheet FS-100-98, 1998, p. 4.
[39] USGS, United States Geological Survey, National Water Information System data available on the World Wide Web (USGS Water Data for the Nation). http://waterdata.usgs.gov/usa/nwis/uv?site_no=02469761 (last accessed 27.03.14.).
[40] J.G. Arnold, R. Srinivasan, R.S. Muttiah, J.R. Williams, Large area hydrologic modeling and assessment: part I. Model development, J. Am. Water Resour. Assoc. 34 (1) (1998) 73–89.
[41] USDA-NRCS, United State Department of Agriculture-Natural Resources Conservation Service. http://datagateway.nrcs.usda.gov/GDGHome.aspx (last accessed January 2014).
[42] NCDC, National Climate Data Center of National Oceanographic and Atmospheric Administration. http://www.ncdc.noaa.gov/oa/ncdc.html (last accessed January 2014).
[43] USDA-NRCS, United State Department of Agriculture-Natural Resources Conservation Service. US General Soil Database (STATSGO). http://websoilsurvey.nrcs.usda.gov (last accessed January 2014).
[44] X. Wang, A. Melesse, Effects of STATSGO and SSURGO as inputs on SWAT models snowmelt simulation, J Am. Water Resour. Assoc. 42 (5) (2006) 1217–1236.
[45] USGS, US Geological Survey, National Land Cover Dataset (NLCD), 2001. http://www.mrlc.gov/index.php (last accessed January 2014).
[46] Hawth's Tools Random Selection Sampling Module. http://www.spatialecology.com/htools/rndsel.php (last accessed January 2014).
[47] J.C. Rojas, Factors Influencing Responses of Loblolly Pine Stands to Fertilization, North Carolina State University, 2005 (PhD dissertation).
[48] E.J. Jokela, P.M. Dougherty, T.A. Martin, Production dynamics of intensively managed loblolly pine stands in the southern United States: a synthesis of seven long-term experiments, For. Ecol. Manage. 192 (2004) 117–130.
[49] N.O. von Stackelberg, G.M. Chescheir, R.W. Skaags, D.M. Amatya, Simulation of the hydrologic effects of afforestation in the Tacuarembo River Basin, Uruguay, Trans. ASABE 50 (2007) 455–468.
[50] R.L. Amateis, H.E. Burkhart, FASTLOB3.0: a Stand-level Growth and Yield Model for Fertilized and Thinned Loblolly Pine Plantations, Forest Modeling Research Cooperative, Virginia Tech, Blacksburg, VA, 2009, p. 38.
[51] A. Van Griensven, T. Meixner, S. Grunwald, T. Bishop, M. Diluzio, R. Srinivasan, A global sensitivity analysis tool for the parameters of multi-variable catchment models, J. Hydrol. 324 (2006) 10–23, http://dx.doi.org/10.1016/j.jhydol.2005.09.008.
[52] D.N. Moriasi, J.G. Arnold, M.W. Van Liew, R.L. Bingner, R.D. Harmen, T.L. Vieth, Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, Trans. ASABE 50 (3) (2007) 885–900.
[53] J.G. Arnold, D.N. Moriasi, P.W. Gassman, K.C. Abbaspour, M.J. White, R. Srinivasan, C. Santhi, R.D. Harmel, A. van Griensven, M.W. Van Liew, N. Kannan, N.K. Jha, SWAT: model use, calibration, and validation, Trans. ASABE 55 (4) (2012) 1491–1508.
[54] R.H. McCuen, Z. Knight, A.G. Cutter, Evaluation of the Nash-Sutcliffe efficiency index, J. Hydraul. Eng. 11 (2006) 597–602.
[55] J.M. Albaugh, E.B. Sucre, Z.H. Leggett, J.-C. Domec, J.S. King, Evaluation of intercropped switchgrass establishment under a range of experimental site

preparation treatments in a forested setting on the Lower Coastal Plain of North Carolina, U.S.A. Biomass Bioenergy 46 (2012) 673–682.

[56] A. Susaeta, P. Lal, J. Alavalpati, E. Mercer, D. Carter, Economics of intercropping loblolly pine and switchgrass for bioenergy markets in the southeastern United States, Agroforest Syst. 86 (2012) 287–298.

[57] Minick KJ, Strahm BD, Fox TR, Sucre EB, Leggett ZH. Microbial nitrogen cycling responses to forest-based bioenergy production. Ecol. Appl. (in press), http://dx.doi.org/10.1890/14-1745.1.

[58] E. Schilling, Compendium of Forestry Best Management Practices for Controlling Nonpoint Source Pollution in North America, Technical Bulletin No. 966, National Council for Air and Stream Improvement, Inc, Research Triangle Park, NC, 2009.

[59] J. Nettles, M. Youssef, J. Cacho, J. Grace, Z. Leggett, E. Sucre, The water quality and quantity effects of biofuel operations in pine plantations of the southeastern USA, in: Water Quality: Current Trends and Expected Climate Change Impacts, Proceedings of Symposium H04 Held during IUGG 2011, Melbourne, Australia, IAHS Publ, July, 2011, p. 348.

[60] J.R. Kiniry, K.A. Cassida, M.A. Hussey, J.P. Muir, W.R. Ocumpaugh, J.C. Read, R.L. Reed, M.A. Sanderson, B.C. Venuta, J.R. Williams, Switchgrass simulation by the ALMANAC model at diverse sites in the southern US, Biomass Bioenergy 29 (2005) 419–425.

[61] C.J. Vorosmarty, C.A. Federer, A.L. Schloss, Evaporation functions compared on US watersheds: possible implications for global-scale water balance and terrestrial ecosystem modeling, J. Hydrol. 207 (1998) 147–169.

[62] D.M. Amatya, R.W. Skaggs, J.D. Gregory, Effects of controlled drainage on the hydrology of drained pine plantations in the North Carolina coastal plain, J. Hydrol. 181 (1) (1996) 211–232.

[63] D.M. Amatya, R.W. Skaggs, Hydrologic modeling of a drained pine plantations on poorly drained soils, Forensic Sci. 47 (1) (2001) 103–114.

[64] J.B. Fisher, R.J. Whittaker, Y. Malhi, ET come home: potential evapotranspiration in geographical ecology, Glob. Ecol. Biogeogr. 20 (2011) 1–18.

[65] S. Tian, M.A. Youssef, R.W. Skaggs, D.M. Amatya, G.M. Chescheir, Modeling water, carbon, and nitrogen dynamics for two drained pine plantations under intensive management practices, For. Ecol. Manage. 264 (2012) 20–36.

[66] Tian S, Youssef MA, Sun G, Chescheir GM, Noormets A, Amatya DM, Skaggs RW, Kimf JS, McNulty S, Gavassi M, Miao G, Domec J-C. Testing DRAINMOD-FOREST for predicting evapotranspiration in a mid-rotation pine plantation. For. Ecol. Manage. (in press).

[67] L. Zhang, W.R. Dawes, G.R. Walker, Response of mean annual evapotranspiration to vegetation changes at catchment scale, Water Resour. Res. 37 (2001) 701–708.

[68] R.W. Skaggs, G.M. Chescheir, G.P. Fernandez, D.M. Amatya, J. Diggs, Effects of land use on soil properties and hydrology of drained coastal plain watersheds, Trans. ASABE 54 (4) (2011) 1357–1365.

[69] Y. Wu, S. Liu, Impacts of biofuels production alternatives on water quantity and quality in the Iowa River Basin, Biomass Bioenergy 36 (2012) 182–191.

[70] J.M. Albaugh, J.C. Domec, C.A. Maier, E.B. Sucre, Z.H. Leggett, J.S. King, Gas exchange and stand-level estimates of water use and gross primary productivity in an experimental pine and switchgrass intercrop forestry system on the Lower Coastal Plain of North Carolina, U.S.A, Agric. For. Meteorol. 192–193 (2014) 27–40.

[71] G.F. McIsaac, M.B. David, C.A. Mitchell, Miscanthus and switchgrass production in central Illinois: impacts on hydrology and inorganic nitrogen leaching, J. Environ. Qual. 39 (2010) 1790–1799.

[72] R.H. Skinner, P.R. Adler, Carbon dioxide and water fluxes from switchgrass managed for bioenergy production, Agric. Ecosyst. Environ. 138 (2010) 257–264.

[73] P.V.V. Le, P. Kumar, D.T. Drewry, Implications for the hydrologic cycle underclimate change due to the expansion of bioenergy crops in the Midwestern United States, Proc. Natl. Acad. Sci. U. S. A. 108 (2011) 15085–15090.

[74] G.C. Hickman, A. Vanloocke, F.G. Dohleman, C.J. Bernacchi, A comparison of canopy evapotranspiration for maize and two perennial grasses identified as potential bioenergy crops, GCB Bioenergy 2 (2010) 157–168.

[75] P. Wagle, V.G. Kakani, Growing season variability in evapotranspiration, ecosystem water use efficiency, and energy partitioning in switchgrass, Ecohydrology (2012), http://dx.doi.org/10.1002/eco.1322. wileyonlinelibrary.com.

[76] J.M. Bosch, J.D. Hewlett, A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration, J. Hydrol. 55 (1982) 3–23.

[77] V. Sahin, M.J. Hall, The effects of afforestation and deforestation on water yields, J. Hydrol. 178 (1996) 293–309.

[78] G. Katul, C.T. Lai, K. Schafer, B. Vidakovic, J. Albertson, D. Ellsworth, R. Oren, Multiscale analysis of vegetation surface fluxes: from seconds to years, Adv. Water Resour. 24 (2001) 1119–1132.

[79] B.E. Law, E. Falge, L. Gu, D.D. Baldocchi, P. Bakwin, P. Berbigier, K. Davis, A.J. Dolman, M. Falk, J.D. Fuentes, A. Goldstein, A. Granier, A. Grelle, D. Hollinger, I.A. Janssens, P. Jarvis, N.O. Jensen, G. Katul, Y. Mahli, G. Matteucci, T. Meyers, R. Monson, W. Munger, W. Oechel, R. Olson, K. Pilegaard, K.T. Paw, H. Thorgeirsson, R. Valentini, S. Verma, T. Vesala, K. Wilson, S. Wofsy, Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation, Agric. For. Meteorol. 113 (2002) 97–120.

[80] A.E. Brown, L. Zhang, T.A. McMahon, A.W. Western, R.A. Vertessy, A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation, J. Hydrol. 310 (2005) 28–61.

[81] (a) E.A. Johnson, J.L. Kovner, Effect on streamflow of cutting forest understory, For. Sci. 2 (1956) 82–91;
(b) K.F. Wenger (Ed.), Forestry Handbook, second ed., John Wiley and Sons, New York, NY, 1984.

[82] R.A. Newbold, V.C. Baldwin, G. Hill, Weight and Volume Determination for Planted Loblolly Pine in North Louisiana, Research Paper SRS-26, NC USDA Forest Service: Southern Research Station, Asheville, 2001.

[83] J.M. Vose, H.L. Allen, Leaf area, stemwood, and nutrition relationships in loblolly pine, For. Sci. 34 (3) (1988) 547–563.

[84] E.L. Stone, P.J. Kalisz, On the maximum extent of tree roots, For. Ecol. Manage. 46 (1991) 59–102.