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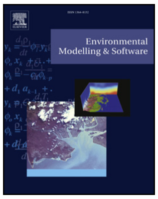

Development and improvement of the simulation of woody bioenergy crops in the Soil and Water Assessment Tool (SWAT)

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ABSTRACT

Quantifying *Populus* growth and the impacts on hydrology and water quality are important should it be widely planted. Soil and Water Assessment Tool (SWAT) tree growth algorithms and parameters for hybrid poplar in Midwestern US and cottonwood in Southern US were improved. Tree growth representation led to SWAT2012 code changes including a new leaf area parameter (TREED), new leaf area index algorithm, and leaf biomass algorithm. Simulated hybrid poplar LAI and aboveground woody biomass (P_{BIAS}: 34 - 5%, NSE: 0.51–0.99, and R^2: 0.72–0.99), and cottonwood aboveground biomass, runoff, sediment, and nitrate-N (P_{BIAS}: 39 - 11%, NSE: 0.86–0.99, and R^2: 0.93–0.99) from the modified SWAT were satisfactory. Improved algorithms, and parameter values and potential ranges for *Populus* were reasonable. Thus, the modified SWAT can be used for *Populus* biofeedstock production modeling and hydrologic and water quality response to its growth.

1. Introduction

Sustainability, energy independence and security, and other social and environmental concerns have prompted an increasing interest in bioenergy as renewable energy sources (Liu et al., 2014; Love and Nejadhashemi, 2011; Sarkar and Miller, 2014; Sarkar et al., 2011; Wu et al., 2012; Wu and Liu, 2012). In particular, cellulosic perennial crops and short-rotation intensive culture (SRIC) of trees are potential sources of biofeedstock for bioenergy production (Anderson et al., 1983; Fege et al., 1979; Guo et al., 2015; Hansen and Baker, 1979; U. S. Department of Agriculture, 1980; Zavitkovski, 1978). *Populus* is highly productive under SRIC, because of its rapid growth, and coppice regeneration (Hansen, 1983), and it could serve as a predominant temperate zone crop with the worldwide improvement of woody biomass/fuel crop species (Haissig et al., 1987). Tree biomass production often increases with the decrease of tree spacing in SRIC plantations, and tree spacing could influence the time needed to reach the maximum mean annual biomass increment (MABI) (Cannell and Smith, 1980; Hansen and Baker, 1979; Strong and Hansen, 1993).

Populus under SRIC systems has environmental impacts (Sixto et al., 2014), including changes in nutrient cycle, soil quality, and water and sediment movement. Sediment loss from a cottonwood site (2.3 Mg/ha) was lower than that from a conventional tilled cotton site (16.2 Mg/ha) over 14 months in Mississippi (Thornton et al., 1998). Nutrient movement from woody crops was less than agricultural crops in the years after the establishment year (Thornton et al., 1998; Tolbert et al., 1997). Aditya and William (2010) demonstrated that planting fast growing poplar trees could decrease total nitrogen (N) and phosphorus (P) loading in the Millsboro Pond Watershed.

Populus growth prediction is essential for managers and policy makers to establish and manage *Populus* under SRIC plantations (Guo et al., 2015). Numerous tree growth models have been used for *Populus* growth simulation to assist with establishment and management of *Populus* under SRIC systems. For example, Ek (1979) applied a regression model to estimate *Populus* branch mass, which was more accurate than models based on branch diameter. Isebrands et al. (1982) used FOREST, an individual-tree-based stand simulation model originally designed for conventional forests, to simulate hybrid poplar growth based on tree size and survival. Tree survival estimation in the FOREST was based on a competition index, which was a function of tree height

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and density, radius and projection overlap of crown, and area of tree horizontal crown projection (Isebrands et al., 1982; Rennolls and Blackwell, 1988). The competition index in the FOREST model was modified to be a function of tree density and crown radius, and the differences between measured and simulated values of hybrid poplar biomass yields were reduced (Meldahl, 1979; Rennolls and Blackwell, 1988). There is a long history of bottom-up modeling for poplar (*Populus*) based on tree inventory and field data (Ceulemans, 1990; Hansen, 1983; Liski et al., 2014; Stettler and Bradshaw, 1994). Host et al. (1990) linked an ecophysiologic growth process model (ECOPHYS) with the Environmental Policy Integrated Model (EPIC) (Williams et al., 1989) to estimate poplar growth and management impacts on site productivity and erosion. A harmonized equation was used for predicting hybrid poplar woody biomass in the Pacific Northwest (Clendenen, 1996). Stand to Ecosystem CaRbon and EvapoTranspiration Simulator (SECRETS) (Deckmyn et al., 2004) and Physiological Principles to Predict Growth (3 PG) (Amichev et al., 2010, 2011) were used for simulating field-scale effects of soil, irrigation, N fertilization and rotation cycle on biomass yields for poplar and aspen. Wang et al. (2013) predicted yield potential of poplar plantations using the Ecosystem Demography 2 (ED2) model and demonstrated that simulated poplar yield matched observed data well.

Biomass is assumed proportional to the radiant energy absorbed by the plant canopy in an energy conversion model, which has been used for simulation of biomass yields of *Populus* (Landsberg and Wright, 1989). The energy conversion equation (Landsberg and Wright, 1989) was also used in Soil and Water Assessment Tool (SWAT), Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMANAC), EPIC, and Agricultural Policy/Environmental eXtender (APEX) models (Guo et al., 2015).

Simulation models have been enhanced and updated in various ways in recent years. For example, the EPIC (Williams et al., 1984, 1989) crop growth model was added in SWAT to account for growth annual variation, auto-fertilization and auto-irrigation as management options (Neitsch et al., 2011). SWAT has been used for simulating impacts of bioenergy crops on hydrology and water quality at a wide range of scales around the world (Boles, 2013; Love and Nejadhashemi, 2011; Nair et al., 2011; Parajuli and Duffy, 2013; Powers et al., 2011; Raj, 2013).

The fundamental concepts of plant algorithms used in SWAT (Arnold et al., 2012) are identical to those used in the ALMANAC model (Kiniry et al., 1992). Plant growth simulation processes of both ALMANAC and SWAT include light interception, leaf area development and conversion of intercepted light into biomass (Kiniry et al., 2008, 2012; Neitsch et al., 2011). Biomass is calculated based on light interception using Beer's law with species-specific radiation use efficiency (BIO_E, amount of dry biomass produced per unit of intercepted light) values (Guo et al., 2015; Kiniry et al., 1999, 2007). A summary of algorithms for estimation of LAI and weight of dropping leaves, and SWAT parameters are included in Data A.1.

SWAT and similar process-based models, such as Agricultural Policy/Environmental eXtender (APEX), have been used to assess the influence of land use management and requires various input parameters for plants (Arnold et al., 2012; Elobeid et al., 2013; Feng et al., 2015; Singh and Saraswat, 2016; Tian et al., 2016). Some researchers have investigated parameterization and improvement of the plant dataset in the SWAT model. For example, Raj (2013) developed and improved the parameters of switchgrass (*Panicum virgatum* L.) and giant miscanthus (*Miscanthus* × *giganteus*) in the SWAT plant dataset, and validated and analyzed the range of parameters for these two grasses. The parameters representing perennial rhizomatous grasses, switchgrass and miscanthus, were used for simulating bioenergy crop growth and hydrologic impact in SWAT (Boles, 2013; Cibin and Chaubey, 2015; Raj, 2013). The parameters representing tree growth in the SWAT plant dataset were developed based on personal communication, and could be improved by tree growth data from the scientific literature (Arnold et al., 2012). Forest management was incorporated and modified in SWAT to better model water quantity and quality in watersheds in forested ecosystems (Li et al., 2008). However, the modification of forest management in the model was for mixed forest systems rather than a specific species (Li et al., 2008). Leaf area development in the model is a function of the growing season for mature plants, which can attain the stand maximum leaf area index (LAI) during the growing season (Arnold et al., 2011). The leaf area algorithm in the model was not applicable for tree growth before maturity, since LAI of young regenerations cannot reach stand maximum LAI before canopy closure (Guo et al., 2015). Thus, SWAT2012 (Revision 635) and prior versions can only be used for growth simulation for mature plants, and the ability to simulate tree biomass yields before maturity is limited (Arnold et al., 2011). Woody crops under SRIC systems are generally harvested before maturity or once they reach maturity (Hansen, 1983). Therefore, it is necessary to improve simulation of tree growth in SWAT.

This study focused on the improvement of the SWAT model to better estimate *Populus* biomass yields and effects of *Populus* on water quantity and quality. This study is the first to improve *Populus* growth algorithms and parameters in SWAT with published *Populus* growth and water quantity and quality data. The objectives of this study were to: (1) improve the plant growth subroutine of SWAT based on new algorithms and growth parameters of hybrid poplar 'Tristis #1' (*Populus balsamifera* L. × *P.tristis* Fisch) and eastern cottonwood (*Populus deltoides* Bartr.) that were created in a prior study with ALMANAC; (2) perform sensitivity analysis and calculate relative sensitivity coefficients of plant growth parameters to model outputs to quantify the effect of *Populus* growth parameters on biomass yield, water yield, and plant uptake of N and P; (3) calibrate the model to match LAI and woody biomass of hybrid poplar in Wisconsin and aboveground biomass of cottonwood in Mississippi; and (4) test the modified model based on comparison of simulated LAI, biomass, runoff, sediment and nitrate-N results of *Populus* with published values.

2. Materials and methods

2.1. Hybrid poplar site in Wisconsin and cottonwood site in Mississippi

Populus growth and water quantity and quality data used in this study were obtained from studies conducted in two sites: a hybrid poplar site in Wisconsin and cottonwood site in Mississippi (Fig. 1). The selected hybrid poplar study site was a SRIC system at the USDA Forest Service Harshaw Experimental Farm near Rhinelander, Wisconsin, USA (45.6° N, 89.5° W) (Hansen and Baker, 1979), on a Padus series loam soil with slope steepness less than 1% to provide a venue for experiments with planted *Populus* plantation (Nelson and Michael, 1982). Eight-inch hybrid poplar cuttings were planted in early June 1970, on a site in the Hugo Sauer Nursery near Rhinelander, Wisconsin (Ek and Dawson, 1976a). The site was sowed to rye, plowed, and rototilled before planting. The nutrients in the stand were maintained as: pH 6.7–7.0; and P 213–224 kg/ha; N was maintained at 3.2% in new leaf tissue; soil moisture at 16–30% levels by irrigation; weeds were controlled using Linuron (Ek and Dawson, 1976a; Michael et al., 1988).

The Tennessee Valley Authority (TVA) region, a 276 county area including all of Tennessee and portions of 10 contiguous states in the southeastern US, was shown to be viable for cost effective production of short-rotation woody crops based on economic analyses (Downing and Graham, 1993). The Delta Research and Extension Center at Stoneville, Mississippi (33.34° N, 90.85°W) in the Tennessee Valley region was selected for cottonwood planting (Joslin and Schoenholtz, 1997). The cottonwood site was on agricultural land dominated by a Bostket silt loam soil. The site has a slope of 0.2–0.3%, and parent material of Riverine sediments. Soil physical property changes were determined at the site in 1995 prior to tree establishment and again in 1997 (the end of growing season). The site included six small 0.25–2 ha

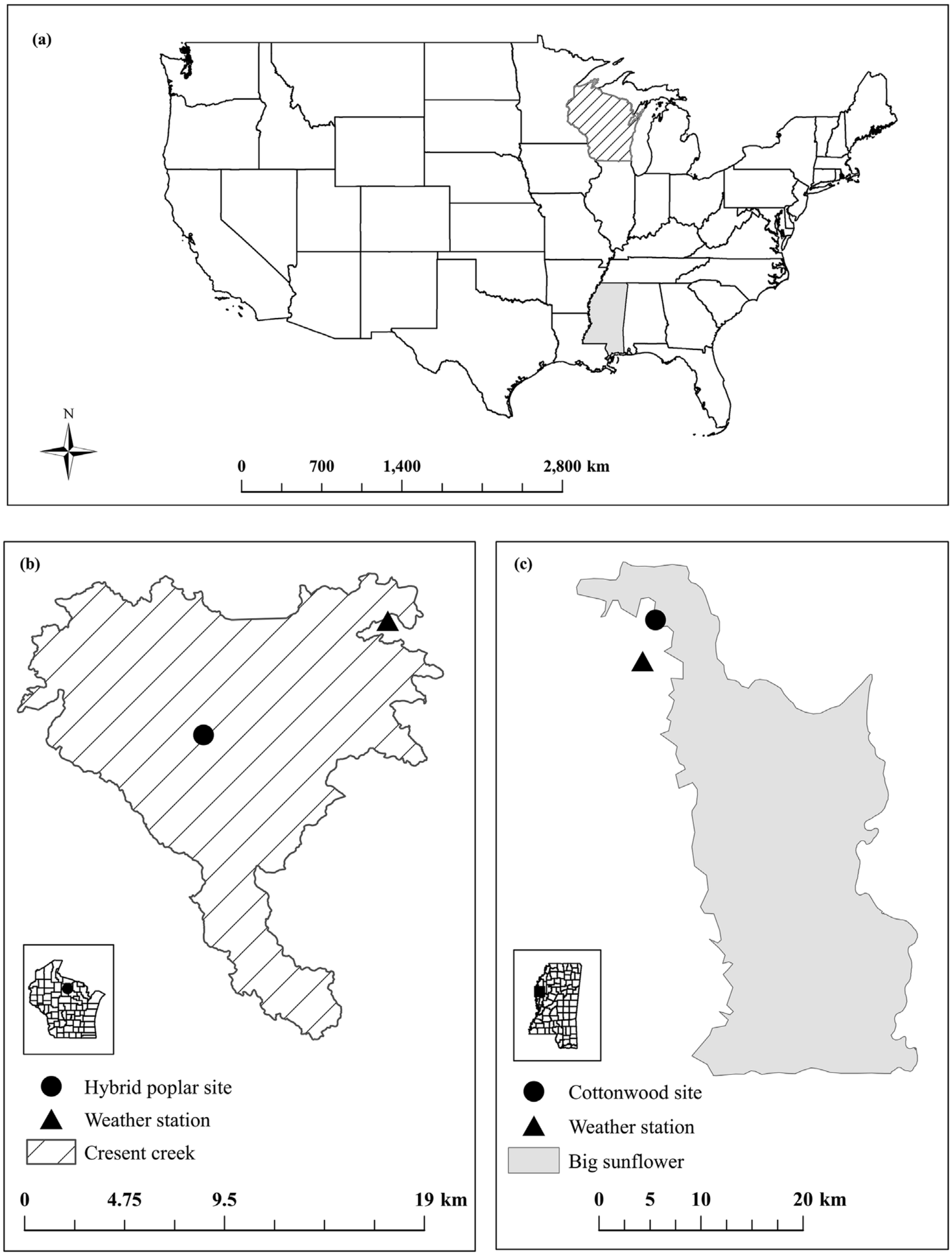

Fig. 1. The hybrid poplar site in Crescent Creek-Wisconsin River Watershed in Wisconsin (b) and the cottonwood site in Big Sunflower River Watershed in Mississippi (c) in the continental U.S. (a).

($0.0025–0.02\,km^2$) replicated watersheds with the same soil type, slope, and land use (Joslin and Schoenholtz, 1997). The establishment of replicated watersheds was essential for the quantity, quality, and timing of surface runoff comparison. Eastern cottonwood (3-year rotation) is a frequently recommended woody species for SRIC systems in the southeastern U.S. (Downing and Graham, 1993). Cottonwood cuttings 20–30 cm long were planted with spacing of 1.2 × 3.6 m (population: 23 trees/100 m^2) on February 3, 1995 (Thornton et al., 1998). The artificial watersheds were formed using 0.5 m high berms to surround land areas (Joslin and Schoenholtz, 1997). Each outlet had a 0.5 m H-shaped flume with a flow meter and an automated flow-proportional sampler, and a 2 m flume section (Joslin and Schoenholtz, 1997). Four 91 cm length × 61 cm width × 8 cm depth pan lysimeters were installed in each plot at 80 cm depth to measure water flux and nutrients. Water samples were collected by the flow proportional sampler for sediment and nutrient concentration in runoff from May 1995 to June 1997 (Joslin and Schoenholtz, 1997).

2.2. Tree growth modification and related code changes in SWAT

The ALMANAC model was previously modified to simulate LAI and biomass yield of hybrid poplar in Wisconsin and cottonwood in Mississippi (Guo et al., 2015). The functional components and parameter values of hybrid poplar were determined, and related algorithms were changed in the model. Since SWAT and ALMANAC use similar plant algorithms (Arnold et al., 2012; Kiniry et al., 1992), tree growth modification in ALMANAC can also be used in SWAT. Thus, related source code on LAI and mass of dropping leaves algorithms (Guo et al., 2015) were changed in SWAT2012 (revision 628). A new leaf area algorithm was added in SWAT and used for maximum seasonal LAI calculation (Equation (1) and (2)), which was useful for simulating tree growth prior to maturity (Guo et al., 2015). A new tree leaf area parameter, TreeD, was added in the plant database, to describe how LAI increases to the maximum potential LAI (BLAI) with varying densities. An algorithm used for calculating dropping leaves weight was added to estimate leaf dropping as a user defined fraction of annual accumulated tree biomass instead of total aboveground biomass (Equation (3)) (Guo et al., 2015). The tree growth algorithm and parameter to simulate leaf area development and leaf biomass were improved, and related code was changed in the subroutines (Table A1).

$$\mathrm{LAI}_{\text{current year}} = \mathrm{LAI}_{\text{current year}-1} \times 10^{\mathrm{RateTree}} \tag{1}$$

$$\mathrm{RateTree} = \log_{10}(\text{current year}/\mathrm{CLAIYR}) \times \mathrm{TreeD} \tag{2}$$

Where CLAIYR is number of years until maximum LAI is attained (for any species), and TreeD is a tree parameter defining how LAI increases up to BLAI.

$$\mathrm{FALF} = \mathrm{BIO\_LEAF}{*}\mathrm{TreeBioIni} \tag{3}$$

Where FALF is weight of dropping leaves, TreeBioIni is annual accumulated tree biomass, and BIO_LEAF is a user defined fraction in plant.dat.

The modified SWAT code and executable file are available for downloading (Data A.2). The SWAT2012 model with tree growth modification was called “modified SWAT” in this study.

2.3. The modified SWAT model setup and management practices

The modified SWAT model was applied using data for Crescent Creek-Wisconsin River watershed in Wisconsin and Big Sunflower River watershed in Mississippi using ArcSWAT in ArcGIS 10.1. Hydrologic Response Units (HRUs) were used to represent the hybrid poplar and cottonwood sites. HRUs were defined for the hybrid poplar and cottonwood sites using the following thresholds: 0% land use, 0% soil, and 0% elevation.

Daily precipitation, and maximum and minimum temperatures data from 01/01/1965 to 12/31/1995 at the Rhinelander WI US weather station (GHCND: USC00477113, Latitude: 45.63, Longitude: −89.42, Elevation: 476 m) close to the hybrid poplar site were downloaded from the National Climatic Data Center (NCDC). Daily precipitation, and maximum and minimum temperature data from 01/01/1992 to 12/31/1997 at the Stoneville experimental station MS US (GHCND: USC00228445, Latitude: 33.4, Longitude: −90.92, Elevation: 39 m) close to the cottonwood site were also obtained from the NCDC. These data were added into ArcSWAT for model setup. Other weather data, including solar radiation, relative humidity and wind speed were generated by the weather geodatabase (WGEN_US_COOP_1960_2010) within SWAT. The primary data required for SWAT model setup and simulation for these two sites came from a variety of sources (Table 1).

The management operation schedules in SWAT include planting and end of schedule dates, tillage, nutrient and pesticide application rates and auto-irrigation. Management practices during the establishment year for each site included tillage and nutrient application data (Tables A2 and A3). Hybrid poplar growth from 1971 to 1980 also included the same N and P application as that in 1970 (Table A2). Planting of hybrid poplar was on 1 June 1970, and harvest and kill were on 1 May 1980 (Ek, 1979; Hansen, 1983). Cottonwood growth from 1996 to 1997 included the same N and P application as that in the establishment year (Table A3). Planting of cottonwood was on 3 Feb 1995, and harvest and kill were on 30 Nov 1997 (Joslin and Schoenholtz, 1997). The management data from the field site did not include exact values for all the input data in SWAT. Thus, N, P, and auto-irrigation application included in model management practices were used to simulate an idealized condition under which *Populus* growth has little water or nutrient stress (Ek, 1979; Guo et al., 2015; Hansen, 1983).

2.4. Sensitivity analysis for the modified SWAT model

Sensitivity analysis for tree growth parameters was performed based on the one-at-a-time (OAT) (and global) approach (James and Burges, 1982) to identify the effect of hybrid poplar growth parameters on biomass yield, water yield, and plant uptake of N and P. The Latin hypercube sampling (LHS) method was used to generate a sample of plausible collections (200 equally distributed samples) of parameter values (Helton and Davis, 2003; Leta et al., 2016). The partial effect of each sample for each tree growth parameter were also calculated (Van Griensven et al., 2006), to mathematically compare each parameter influence on a predicted output and obtain the rank of sensitivity to different model outputs based on the average partial effects of 200 samples (Equation (4)). Higher rank represented higher sensitivity and lower rank meant lower sensitivity (Leta et al., 2016; Van Griensven et al., 2006). The results of sensitivity analysis can provide guidance for determination of realistic values or potential ranges for parameters and model calibration.

$$Sensitivity_{ij} = \left| \frac{100 \times (y_{ij} - y_0)/((y_{ij} + y_0)/2)}{(x_{ij} - x_{i0})/x_{i0}} \right| \tag{4}$$

Where $Sensitivity_{ij}$ is the partial effect of parameter i and sample j, x_{i0} is the initial value of parameter i, y_0 is the value of the model output based on the initial value for all parameters, x_{ij} is the value of parameter i for sample j, and y_{ij} is the value of the model output based on x_{ij}.

2.5. Data used for model calibration and validation

The model was run for a total of 16 years (1965–1980) at the hybrid poplar site and 6 years (1992–1997) at the cottonwood site. The first 5 years (1965–1969) at the hybrid poplar site and the first 3 years (1992–1994) at the cottonwood site were used for model warm-up. Simulated LAI and biomass yield data from 1970 to 1980 at the hybrid poplar site were compared with the observed data for model calibration and validation. Simulated biomass yield data from 1995 to 1997 and simulated water quantity and quality data from 1995 to 1997 at the cottonwood site were compared with the observed data for model calibration.

Three observed data sets of hybrid poplar growth, cottonwood growth, water quantity and water quality (sets 1, 2 and 3) were used for model calibration and validation (Table 2). In this study, the LAI and biomass yield data for hybrid poplar in Wisconsin were separated into two datasets, sets 1 and 2, which were used for model calibration and validation, respectively (Table 2). We used hybrid poplar data with high, medium and low densities for both of model calibration and validation, which were similar with Guo et al. (2015)'s study. Set 1 data, LAI and aboveground woody biomass data for hybrid poplar with high density (population: 278 trees/100 m^2) and low density (population: 17 trees/100 m^2), and aboveground woody biomass data of hybrid poplar with medium density (population: 69 trees/100 m^2), were used for hybrid poplar model calibration (Table 2). Set 2 data, aboveground woody biomass and LAI of hybrid poplar with high density (population: 83 trees/100 m^2) and medium density (population: 25 trees/100 m^2), and aboveground woody biomass data of hybrid poplar with high density (population: 1111 trees/100 m^2) and low density (population: 8 trees/100 m^2), were used for hybrid poplar model validation (Table 2). Set 3 data were all observed data in the cottonwood site in Mississippi, including aboveground biomass, seasonal mean runoff per runoff event, seasonal mean sediment per runoff event, seasonal total sediment, seasonal mean nitrate-N in runoff and seasonal total nitrate-N in runoff. Only model calibration was performed with the set 3 data at this site, since only one tree population of 23 trees/100 m^2 (medium density) was available for the cottonwood plot (Table 2).

Table 1
Data for hybrid poplar growth simulation in Wisconsin and water quantity and quality impacts of cottonwood growth in Mississippi by SWAT.

Data	Source	Period	
		Wisconsin	Mississippi
Elevation (30 m)	USGS[a] National Map Viewer		
SSURGO[b]	USDA[c] Web Soil Survey		
LULC[d] (30 m)	USGS The National Map Viewer	2006	2006
Daily precipitation (mm)	NCDC[e]	1965–1995	1992–1997
Daily maximum and minimum temperatures (°C)	NCDC	1965–1995	1992–1997
Aboveground woody biomass yields of hybrid poplar (Mg/ha)	Hansen (1983)	1970–1980	
Annual LAI of hybrid poplar	Hansen (1983)	1970–1980	
Aboveground biomass yields of cottonwood (Mg/ha)	Pettry et al. (1997)		1995–1997
Mean runoff per event (m^3/ha) for each season	Thornton et al. (1998)		1995–1996
Mean sediment loss per event (kg/ha) for each season	Thornton et al. (1998)		1995–1996
Seasonal total sediment loss (kg/ha)	Thornton et al. (1998)		1995–1996
Seasonal means of nutrient losses (nitrate-N) (kg/ha)) per runoff event	Thornton et al. (1998)		1995–1996
Seasonal total nutrient losses (nitrate-N) (kg/ha)) in runoff	Thornton et al. (1998)		1995–1996

[a] USGS: U.S. Geological Survey.
[b] SSURGO: Soil Survey Geographic Database.
[c] USDA: U.S. Department of Agriculture.
[d] LULC: Land Use and Land Cover.
[e] NCDC: National Climate Data Center.

2.6. Calibration of the modified SWAT and parameterization

Before calibrating the modified SWAT, values and ranges of some tree growth parameters were obtained from a previous study on *Populus* growth simulation by ALMANAC (Data A.3) (Guo et al., 2015). For hybrid poplar model calibration in Wisconsin, hybrid poplar growth parameters were adjusted manually, and LAI and aboveground woody biomass data for hybrid poplar from the modified SWAT were compared with the hybrid poplar calibration data (set 1) (Hansen, 1983) (Table 2). PHU, BIO_E, EXT_COEF, BLAI, ALAI_MIN, FRGRW1, FRGRW2, CNYLD and CPYLD were modified manually by increasing/decreasing default values by 20% within reasonable ranges (Arnold et al., 2012) to obtain acceptable LAI and aboveground woody biomass results for hybrid poplar with various populations, which matched well with published values during calibration of the modified SWAT (Hansen, 1983).

For cottonwood model calibration in Mississippi, aboveground biomass, seasonal mean runoff per runoff event, seasonal mean sediment per runoff event, seasonal total sediment, seasonal mean nitrate-N in runoff and seasonal total nitrate-N in runoff for cottonwood from the modified SWAT were compared with the cottonwood calibration (set 3). Initial SCS CN II value (CN2), soil erodibility (K) factor (USLE_K), and minimum value of C factor for water erosion (USLE_C) were modified manually by increasing/decreasing default values by 20% within reasonable ranges (Arnold et al., 2011) to obtain acceptable runoff, sediment and nitrate-N in runoff, which matched well with observed values (Joslin and Schoenholtz, 1997). Simulated outputs of the modified SWAT model for the cottonwood site in Mississippi were then compared to observed values.

2.7. Validation of the modified SWAT after calibration and model comparison

For hybrid poplar model validation in Wisconsin, aboveground woody biomass and LAI for hybrid poplar from the modified SWAT after calibration were compared with the hybrid poplar validation data (set 2) (Hansen, 1983) (Table 2). R^2, NSE and percent bias/percent error (P_{BIAS} [%]) were used to evaluate model performance (Kumar and Merwade, 2009). The R^2 value can represent the strength of the linear relationship between simulated and measured data. The NSE value (Nash and Sutcliffe, 1970) can indicate how well the measured data versus simulated data fits the 1:1 line. An R^2 or NSE value of greater than 0.5 is considered reasonable model performance (Moriasi et al., 2007). Percent bias (Gupta et al., 1999) measures the tendency of the simulated data to be larger or smaller than the measured data. Negative values represent model overestimation bias. If P_{BIAS} ± 25% for streamflow, ± 55% for sediment, and ± 70% for N and P, model simulation results can be considered satisfactory (Moriasi et al., 2007).

Table 2
Hybrid poplar and cottonwood growth data for model calibration and validation.

Populus	Set	Population (trees/ 100 m$^{2)}$	Density level	Outputs (aboveground woody biomass (Mg/ha), LAI, runoff (mm), sediment and nitrate-N in runoff (kg/ha))	Data usage
Hybrid poplar[a]	1	278	high	LAI	model calibration
		278	high	aboveground woody biomass	
		69	medium	aboveground woody biomass	
		17	low	LAI	
		17	low	aboveground woody biomass	
	2	1111	high	aboveground woody biomass	model validation
		83	high	LAI	
		83	high	aboveground woody biomass	
		25	medium	LAI	
		25	medium	aboveground woody biomass	
		8	low	aboveground woody biomass	
Cottonwood[b]	3	23	medium	aboveground biomass	model calibration
		23	medium	runoff, sediment and nitrate-N in runoff	

[a] (Hansen, 1983).
[b] (Pettry et al., 1997; Thornton et al., 1998).

To compare the performance of models in simulating biomass yields, the simulated aboveground woody biomass of hybrid poplar with populations of 17 (low density) and 278 (high density) trees/100 m^2 from the modified SWAT were selected to compared with those simulated from the original SWAT. The observed MABI values for hybrid poplar in Wisconsin and the simulated values from FOREST and modified FOREST models from previous studies were used to evaluate the performance of models in simulating MABI (Isebrands et al., 1982; Meldahl, 1979). Simulated MABI from the modified SWAT were compared with the simulated values from the original SWAT in the current research, and the published observed and simulated data from FOREST and modified FOREST models (Isebrands et al., 1982; Meldahl, 1979).

3. Results and discussion

3.1. Sensitivity analysis of hybrid poplar growth parameters to selected outputs by the modified SWAT model of hybrid poplar site in Wisconsin

The effects of hybrid poplar growth parameters on the selected SWAT model outputs (annual biomass yield, water yield, plant uptake of N and P) were analyzed. The "water yield" is the water leaving the HRU representing the hybrid poplar site and entering the main channel. A relative sensitivity coefficient was calculated for each tree growth parameter to obtain the rank of sensitivity to different model outputs (Table 3). Hybrid poplar biomass yield was most sensitive to BIO_E, T_BASE, T_OPT, light extinction coefficient (EXT_COEF), TREED, number of years required for tree species to reach full development (MAT_YRS), and other leaf area development parameters (minimum LAI for plant during dormancy (ALAI_MIN), BLAI, fraction of BLAI corresponding to the second point on optimal leaf development curve (LAIMX2), and fraction of growing season coinciding with LAIMX2 (FRGRW2)). BIO_E, 10 times radiant use efficiency, was the most sensitive parameter for biomass yield of hybrid poplar. Plant biomass was calculated based on light interception and radiant use efficiency, which was the slope of the relationship between cumulative, intercepted photosynthetically active radiation (PAR) and biomass distributed during the growing season (Trybula et al., 2015). Besides BIO_E, EXT_COEF and ALAI_MIN were also important parameters to quantify the fraction of light intercepted by leaves and potential plant growth (Kiniry, 1998). EXT_COEF controlled estimation of the amount of intercepted PAR, and minimum LAI during dormancy, ALAI_MIN, affected leaf area development (Arnold et al., 2012). T_BASE and T_OPT were also sensitive to biomass yield, since they both affected temperature stress and timing of peak biomass yield, and T_BASE also controlled emergence threshold and potential heat units to reach maturity (Arnold et al., 2012; Trybula et al., 2015). Annual water yield and surface runoff were sensitive to BIO_E, T_OPT and T_BASE. Sediment loss in surface runoff was only sensitive to minimum crop factor for water erosion (USLE_C). Nitrate-N loss was sensitive to BIO_E, plant N fraction at maturity (PLTNFR3), hybrid poplar biomass yield, water yield, surface runoff and plant uptake of N and P were highly sensitive to BIO_E and T_OPT (Table 3), which was consistent with sensitivity analysis of switchgrass growth parameters in SWAT (Trybula et al., 2015).

Table 3

Sensitivity analysis of model outputs to tree growth parameters for the modified SWAT in Wisconsin (parameters without sensitivity get rank 22 for biomass (BIO), surface runoff (Q) and plant uptake of nitrogen (PN), rank 24 for water yield and plant uptake of phosphorus (PP), rank 2 for sediment in surface runoff (SD), and rank 12 for nitrate in surface runoff (N)).

Parameter	Parameter definition	BIO	WY	Q	SD	N	PN	PP
		t/ha	mm		kg/ha			
BIO_E	Radiation use efficiency (kg/ha)/(MJ/m^2)	1	1	1	2	1	1	1
T_OPT	Optimal temperature (°C)	2	3	2	2	7	2	2
T_BASE	Base temperature (°C)	3	5	5	2	3	11	11
EXT_COEF	Light extinction coefficient	4	4	4	2	4	4	3
ALAI_MIN	Minimum LAI during dormancy	5	9	8	2	5	6	8
TREED	LAI decline factor	6	6	6	2	11	8	5
MAT_YRS	Years required for trees to reach maturity (years)	7	7	9	2	12	9	6
BLAI	Maximum leaf area index (LAI)	8	8	7	2	10	10	7
LAIMX2	Fraction of BLAI corresponding to 2nd point on optimal leaf development curve	9	10	12	2	12	13	10
FRGRW2	Fraction of growing season coinciding with LAIMX2	10	12	17	2	12	14	12
FRGRW1	Fraction of growing season coinciding with LAIMX1	11	14	20	2	12	15	13
LAIMX1	Fraction of BLAI corresponding to 1st point on optimal leaf development curve	12	15	21	2	12	17	15
WAVP	Rate of decline in radiation use efficiency per unit increase in vapor pressure deficit	13	16	11	2	12	18	18
PLTNFR3	Plant N fraction at maturity	14	19	15	2	2	7	16
PLTNFR1	Plant N fraction at emergence	15	21	18	2	8	5	17
PLTNFR2	Plant N fraction at 50% maturity	16	20	14	2	6	3	19
GSI	Maximum stomatal conductance (m/s)	17	2	3	2	9	12	21
DLAI	Point in growing season when LAI declines	18	18	16	2	12	19	20
CHTMX	Maximum canopy height (m)	19	11	10	2	12	16	22
RDMX	Maximum rooting depth (m)	20	23	22	2	12	21	23
VPDFR	Vapor pressure deficit (kPa) corresponding to 2nd point on the stomatal conductance curve	21	17	19	2	12	20	24
CNYLD	Plant N fraction in harvested biomass	22	24	22	2	12	22	24
CPYLD	Plant P fraction in harvested biomass	22	24	22	2	12	22	24
PLTPFR1	Plant P fraction at emergence	22	24	22	2	12	22	9
PLTPFR2	Plant P fraction at 50% maturity	22	24	22	2	12	22	4
PLTPFR3	Plant P fraction at maturity	22	24	22	2	12	22	14
USLE_C	Water erosion minimum crop factor	22	24	22	1	12	22	24
FRGMAX	Fraction of GSI corresponding to the 2nd point of the stomatal conductance curve	22	13	13	2	12	22	24
CO2HI	Elevated CO_2 concentration (μL CO_2/L air) corresponding the 2nd point in the BIO_E curve	22	24	22	2	12	22	24
BIOHI	Biomass-energy ratio corresponding to 2nd point on the BIO_E curve	22	24	22	2	12	22	24
RSDCO_PL	Residue decomposition coefficient	22	22	22	2	12	22	24
WSYF	Harvest index lower limit ((kg/ha)/(kg/ha))	22	24	22	2	12	22	24
BMX_TREES	Forest maximum biomass (Mg/ha)	22	24	22	2	12	22	24
BM_DIEOFF	Biomass dieoff fraction	22	24	22	2	12	22	24
HVSTI	Optimal harvest index	22	24	22	2	12	22	24

Table 4

Calibrated values and potential parameter ranges for hybrid poplar (*Populus balsamifera* L. × *P.tristis* Fisch) and cottonwood (*Populus deltoides* Bartr.) compared to the current parameters for *Populus* in SWAT2012 plant database. Calibrated values of curve number (CN2) and soil erodibility factor (USLE_K) for hydrological and water quality simulation at the cottonwood site compared to the default value in the model database.

Parameter	*Populus balsamifera* L. × *P.tristis* Fisch (HYPT)		*Populus deltoides* Bartr. (POEC)		*Populus* (POPL)
	Value	Range	Value	Range	Database value
T_BASE[a] [Heat Units to Maturity][a]	4 [1750]	0-6 [2150–1500]	8 [2818]	7-15 [2900–2200]	10 –
T_OPT[b]	25	25–30	25	25–30	30
BIO_E[c,d]	20	20–35	41	30–58	30
EXT_COEF[c,d]	0.30	0.20–0.60	0.60	0.20–0.60	0.45
BLAI[c,e,f]	9.50	5.00–9.50	9.50	5.00–9.50	5.00
LAIMX2[c,e,f]	0.95	0.95–0.98	0.95	0.95–0.98	0.95
DLAI[c,e,f]	0.99	0.99	0.99	0.99	0.99
BIO_LEAF[e]	0.30	0.20–0.40	0.30	0.20–0.40	0.30
TREED[c,e,g]	0.500–4.500	0.500–4.500	0.500–4.500	0.500–4.500	–
FRGRW2[c,e,f]	0.40	0.40–0.45	0.40	0.40–0.45	0.40
ALAI_MIN[c,e,f]	0.00	0.00–0.75	0.00	0.000–0.750	0.75
FRGRW1[c,e,f]	0.05	0.05–0.07	0.05	0.05–0.07	0.05
LAIMX1[c,e,f]	0.05	0.05–0.30	0.05	0.05–0.30	0.05
GSI[b]	0.007	0.004–0.007	0.004	0.004–0.007	0.004
CHTMX[b]	Existing value	7.00–15.00	10.00	10.00–15.00	7.50
CNYLD[c,g,h]	0.0005	0.0005–0.0015	0.0005	0.0005–0.0015	0.0015
CPYLD[c,g,h]	0.0002	0.0002–0.0003	0.0002	0.0002–0.0003	0.0003
WSYF[c]	0.00	0.00	0.00	0.00	0.01
MAT_YRS[e],[f]	6–9	6–9	6–9	6–9	10
HVSTI[i,j]	0.65	0.45–0.70	0.60	0.40–0.65	0.76
USLE_C[c,k]	Existing value	0.001–0.009	0.002	0.001–0.009	0.001
CN2[c,l]	Existing value	0–99	65	0–99	85
USLE_K[c,j]	Existing value	0.01–0.99	0.41	0.01–0.99	0.37

[a] Calculated based on maximum and minimum daily temperature from NCDC weather stations.
[b] Assumption.
[c] Modified value after calibration.
[d] (Landsberg and Wright, 1989).
[e] (Hansen, 1983).
[f] (Zavitkovski, 1981).
[g] (Black et al., 2002).
[h] (McLaughlin et al., 1987).
[i] (Michael et al., 1988).
[j] (Arnold et al., 2011).
[k] (Wischmeier and Smith, 1978).
[l] (Neitsch et al., 2002).

3.2. Values and potential parameter range for Populus growth in the modified SWAT

The calibrated modified SWAT reasonably simulated annual LAI and aboveground woody biomass yield of hybrid poplar with various spacings. During calibration, values and potential parameter ranges for *Populus* were determined (Table 4) (Arnold et al., 2011; Black et al., 2002; Guo et al., 2015; Hansen, 1983; Kiniry et al., 1999; Landsberg and Wright, 1989; MacDonald et al., 2008; McLaughlin et al., 1987; Michael et al., 1988; Zavitkovski, 1981). The default values for parameters PLTPFR1, PLTPFR2, PLTPFR3, PLTNFR1, PLTNFR3, PLTNFR2, FRGMAX, VPDFR, RSDCO_PL, RDMX, WAVP, CO2HI, BIOHI, BMX_TREES and BM_DIEOFF in the plant database were considered reasonable for *Populus* growth simulation (Arnold et al., 2012; Kiniry et al., 1999; MacDonald et al., 2008). Since obtaining enough detailed data about the phenological and physiological characteristics of the vegetation is difficult and time consuming, globally approximated plant parameter ranges are often used in ecological models (Arnold et al., 2012; Neitsch et al., 2011). Values and potential parameter ranges of hybrid poplar and cottonwood (Table 4) can be adjusted when applied to specific regions. These values and ranges also provide guidance for determination of growth parameters for other *Populus* clones or other woody species in process based models. The modified SWAT with the calibrated values for hybrid poplar growth parameters have been used to model biomass yields of hybrid poplar and the impacts on hydrology, and sediment and nutrient losses in the Midwestern watersheds (Cibin et al., 2016; Guo, 2016; Guo et al., 2018a).

3.3. Calibration of the modified SWAT

3.3.1. Calibration of the modified SWAT for hybrid poplar growth in Wisconsin

The calibrated annual LAI and aboveground woody biomass values by the modified SWAT were compared with the set 1 data (Figs. 2 and 3). Overall performance of the calibrated LAI and aboveground woody biomass for the set 1 data were satisfactory (NSE > 0.5 and $R^2 > 0.5$, Table 5). P_{BIAS} values of the calibrated LAI and aboveground woody biomass of hybrid poplar ranged from -9% to 2%, representing accurate model simulation (Table 5). Projected annual LAI for the set 1 data by the modified SWAT fit the measured values reasonably well, except that the projected LAI values at years 8 and 9 (1978 and 1979) were slightly higher than the measured values (population of 17 trees/100 m^2) (Fig. 2b).

Projected annual aboveground woody biomass for the set 1 data by the modified SWAT model reasonably matched measured values, except that projected annual aboveground woody biomass values at years 2 and 3 (1972 and 1973) were higher than observed values (population of 278 trees/100 m^2) (Fig. 3a). Projected aboveground woody biomass values from years 8–10 were slightly higher than measured values (population of 17 trees/100 m^2) (Fig. 3c).

Moreover, the calibrated daily streamflow from the outlet of Tom Doyle Creek-Wisconsin River watershed in Wisconsin reasonably fit the

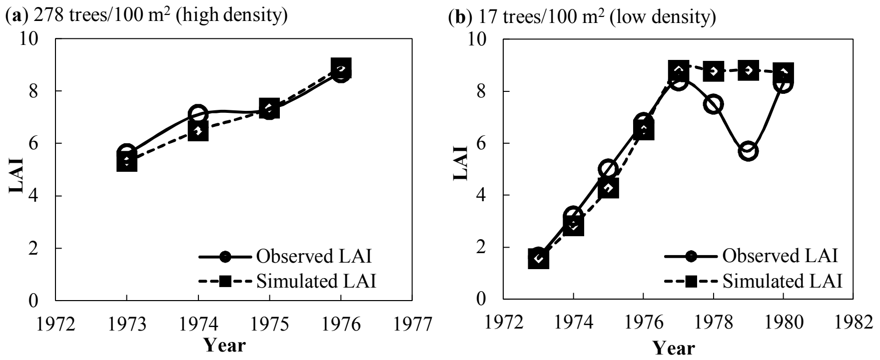

Fig. 2. Yearly observed and calibrated LAI of hybrid poplar with populations of 278 (a) and 17 (b) trees/100 m^2 for the modified SWAT during calibration.

observed data from the USGS Wisconsin River at Rainbow Lake station (05391000, Latitude: 45.83, Longitude: −89.55) (Data A.4, Table A4 and Fig. A1). Overall performance of the calibrated daily streamflow from 1970 to 1980 was satisfactory (P_{BIAS} = 12%, NSE = 0.53 and R^2 = 0.67) from the modified SWAT (Fig. A1). Generally, simulated annual flow partitioning from 1970 to 1980 for the modified SWAT in Wisconsin was also reasonable (Data A.4 and Fig. A2), similar to those for a forest dominated watershed in northern Wisconsin (Vano et al., 2006).

3.3.2. Calibration of the modified SWAT for cottonwood growth and hydrologic and water quality responses in Mississippi

Overall performance of the modeled annual aboveground biomass, seasonal mean runoff per runoff event, seasonal mean sediment per runoff event, seasonal mean nitrate-N in runoff per runoff event, and seasonal total nitrate-N in runoff for the set 3 data were satisfactory (NSE > 0.5 and R^2 > 0.5). The calibrated results of annual aboveground biomass (Fig. 4a), seasonal mean runoff per runoff event (Fig. 4b), seasonal mean sediment per runoff event (Fig. 4c), seasonal mean nitrate-N in runoff per runoff event (Fig. 4e), and seasonal total nitrate-N in runoff (Fig. 4f) of cottonwood growth from the modified SWAT model was similar to observed values. NSE (R^2) values for modeled annual aboveground biomass, seasonal mean runoff per runoff event, seasonal mean sediment per runoff event, seasonal mean nitrate-N in runoff per runoff event, and seasonal total nitrate-N in runoff for the set 3 data were 0.99 (0.99), 0.91 (0.93), 0.98 (0.99), 0.86 (0.98), and 0.97 (0.98), respectively (Table 5). Additionally, P_{BIAS} = 0.8% (close to 0) for the modeled annual aboveground biomass and seasonal total nitrate-N in runoff (Table 5) indicated that simulated biomass yield and seasonal total nitrate-N in runoff values by the modified SWAT were accurate. P_{BIAS} values of the modeled seasonal mean runoff per runoff event, seasonal mean sediment per runoff event, and seasonal mean nitrate-N in runoff per runoff event of cottonwood growth were −12% (P_{BIAS} > - 25%), 11% (P_{BIAS} < 55%), −39% (P_{BIAS} > -70%). P_{BIAS} values of −12% and −39% indicate modeled results were overestimated generally and modeled mean runoff during the fall and winter of 1995 (Fig. 4b) and mean nitrate-N in runoff during the winter of 1995 and the spring of 1996 (Fig. 4e) were higher than the observed values. P_{BIAS} = 11% indicated seasonal mean sediment per runoff event was slightly underestimated and simulated mean sediment during the

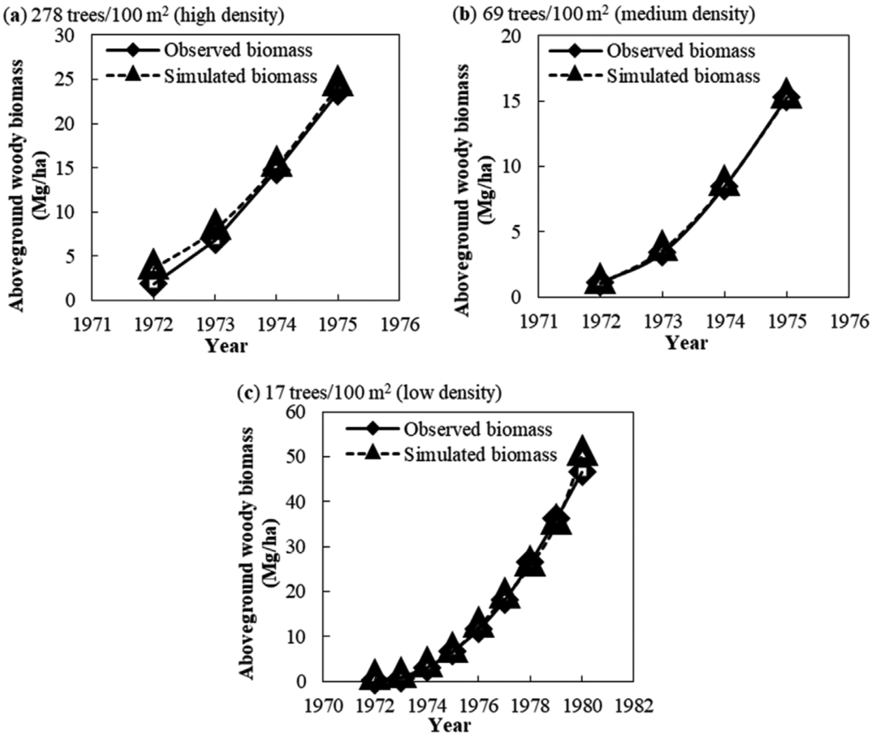

Fig. 3. Yearly observed and calibrated aboveground woody biomass of hybrid poplar with populations of 278 (a), 69 (b) and 17 (c) trees/100 m^2 for the modified SWAT during calibration. Aboveground woody biomass of hybrid poplar used for model calibration includes stem and branch biomass.

Table 5
Performance evaluation of the calibrated results for hybrid poplar in Wisconsin and cottonwood in Mississippi from the modified SWAT.

Populus	Population (trees/100 m^2)	Model outputs	P_{BIAS} (%)	NSE	R^2
Hybrid poplar	278	Annual LAI	2	0.90	0.96
	278	Annual aboveground woody biomass (AWB) (Mg/ha)	−9	0.98	0.99
	69	Annual AWB (Mg/ha)	−1	0.99	0.99
	17	Annual LAI	−8	0.70	0.84
	17	Annual AWB (Mg/ha)	−2	0.99	0.99
Cottonwood	23	Annual aboveground biomass (Mg/ha)	0.8	0.99	0.99
	23	Seasonal mean runoff (mm)	−12	0.91	0.93
	23	Seasonal mean sediment (kg/ha)	11	0.98	0.99
	23	Seasonal total sediment (kg/ha)	60	−0.15	0.42
	23	Seasonal mean nitrate-N (kg/ha)	−39	0.86	0.98
	23	Seasonal total nitrate-N (kg/ha)	0.8	0.97	0.98

spring of 1996 was slightly lower than the observed value (Fig. 4c). Simulated seasonal total sediment by modified SWAT did not fit observed values well, except that modeled total sediment during the fall of 1995 was close to the observed value (Fig. 4d). Simulated total sediment values during the winter of 1995 and the spring of 1996 were lower than the observed values as shown in Fig. 4d. NSE and R^2 values of modeled seasonal total sediment were −0.15 and 0.42 (NSE < 0.5, R^2 < 0.5), which were not satisfactory (Table 5). NSE and R^2 were slightly lower than acceptable limits. P_{BIAS} = 60% (P_{BIAS} > 55%) indicating simulated seasonal total sediment was underestimated. However, simulated seasonal total sediment can still be considered reasonable, since it is challenging to accurately simulate sediment load and capture peaks of sediment load from a mildly sloped plot with low surface runoff and sediment load (Fig. 4b and d) (Guo et al., 2018b).

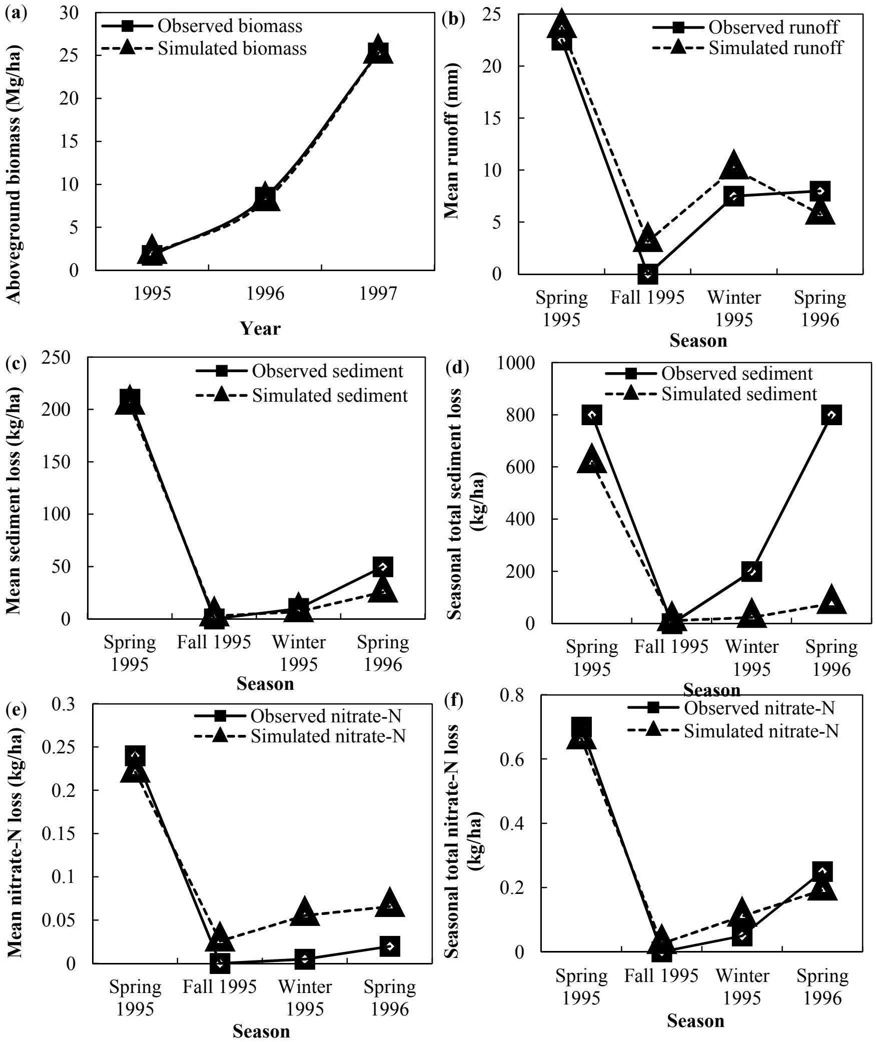

Fig. 4. Observed and calibrated aboveground biomass (a), runoff (b), sediment (c, d) and nitrate-N in runoff (e, f) of cottonwood with population of 23 trees/100 m^2 for the modified SWAT during calibration. Aboveground biomass of cottonwood used for model calibration includes stem, branch and leaf biomass. Annual aboveground biomass of cottonwood, and seasonal runoff, sediment and nitrate-N in runoff data were used for model calibration.

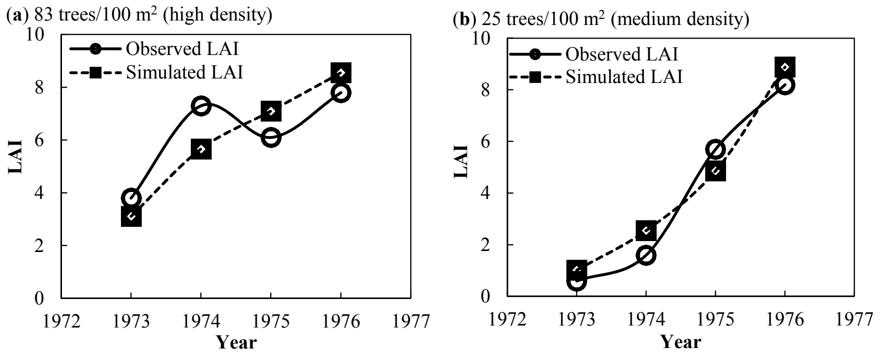

Fig. 5. Yearly observed and calibrated LAI of hybrid poplar with populations of 83 (a) and 25 (b) trees/100 m^2 for the modified SWAT during validation.

3.4. The modified SWAT model validation for hybrid poplar growth in Wisconsin and model comparison

Overall performance of the validated LAI for the set 2 data was satisfactory (NSE $>$ 0.5 and R^2 $>$ 0.5). Simulated annual LAI for the set 2 data by the modified SWAT model fit measured values well (Fig. 5a and b), except that simulated LAI value was slightly lower than the observed value at year 4 (1974), and slightly higher than the observed value at year 5 (1975) (population of 83 trees/100 m^2) (Fig. 5a). P$_{\mathrm{BIAS}}$ values of simulated LAI for the set 2 data were 2% and −8% respectively, indicating accurate model simulation. NSE (R^2) values for simulated LAI of hybrid poplar with populations of 83 and 25 trees/100 m^2 were 0.51 (0.72) and 0.94 (0.95), respectively (Table 6).

Overall performance of the validated aboveground woody biomass yields for the set 2 data was acceptable (NSE $>$ 0.5 and R^2 $>$ 0.5). Simulated annual aboveground woody biomass for the set 2 data by the modified SWAT model was similar to measured values (Fig. 6). P$_{\mathrm{BIAS}}$ values were −31% (1111 trees/100 m^2) and −34% (83 trees/100 m^2), indicating that modeled annual aboveground woody biomass results by the modified SWAT were overestimated. Aboveground woody biomass values were calculated based on simulated total biomass and fraction of total biomass partitioned to tree stems and branches. Overestimation of percentage of hybrid poplar aboveground biomass partitioned to woody biomass would result in larger than observed aboveground woody biomass values.

For aboveground woody biomass from year 2–5 of 1111 trees/100 m^2 hybrid poplar (Fig. 6a), from year 2–4 of 83 trees/100 m^2 hybrid poplar (Fig. 6b), and years 3 and 4 of 25 trees/100 m^2 hybrid poplar (Fig. 6c), simulated values by the modified SWAT were higher than observed values. P$_{\mathrm{BIAS}}$ values were −3% (25 trees/100 m^2) and 5% (8 trees/100 m^2), representing accurate model simulation (Fig. 6d). NSE (R^2) values for modeled aboveground woody biomass of hybrid poplar with populations of 1111, 83, 25, and 8 trees/100 m^2 were 0.55 (0.97), 0.73 (0.97), 0.91 (0.97), and 0.99 (0.99), respectively (Table 6).

Besides NSE, R^2 and P$_{\mathrm{BIAS}}$ values, the nonparametric Wilcoxon rank sum test and Cohen's Effect Size were used for annual LAI and aboveground woody biomass of hybrid poplar with all populations (both the set 1 and set 2 data), to test the equality of the medians and means for the observed and simulated results, respectively (Cohen, 1977; Guo et al., 2018c). The Wilcoxon rank sum test was two-tailed, with a significance level of $P = 0.05$. The Wilcoxon rank sum test results for annual LAI and aboveground woody biomass both showed that there is no significant differences between the medians of the observed and simulated results ($P > 0.05$). Cohen's Effect Size for both annual LAI and aboveground woody biomass were small (< 0.2), representing small differences between the means of the observed and simulated results (Cohen, 1977; Guo et al., 2018c).

Table 6
Performance evaluation of the validated results for hybrid poplar in Wisconsin from the modified SWAT.

Population (trees/100 m^2)	Outputs	P$_{\mathrm{BIAS}}$ (%)	NSE	R^2
1111	AWB (Mg/ha)	−31	0.55	0.97
83	LAI	2	0.51	0.72
83	AWB (Mg/ha)	−34	0.73	0.97
25	LAI	−8	0.94	0.95
25	AWB (Mg/ha)	−3	0.91	0.97
8	AWB (Mg/ha)	5	0.99	0.99

3.5. Evaluation of the modified SWAT in simulating seasonal hybrid poplar growth in Wisconsin and model comparison

To evaluate model performance in simulating seasonal variability of hybrid poplar growth, simulated LAI and total biomass was also compared with the observed data for hybrid poplar in Wisconsin with a population of 278 trees/100 m^2 during the first growing season in 1979 from Michael et al. (1988)'s previous research (Data A.5 and Fig. A3). Generally, the simulated seasonal LAI and total biomass for hybrid poplar reasonably fit the observed data (Data A.5 and Fig. A3). Seasonal changes of simulated LAI and total biomass for 8 trees/100 m^2 hybrid poplar from 2003 to 2017 were reasonable and consistent with seasonal leaf area development and changes of biomass for hybrid poplar in the region (Cibin et al., 2016; Michael et al., 1988) (Data A.5 and Fig. A4).

The simulated aboveground woody biomass of hybrid poplar with populations of 17 and 278 trees/100 m^2 from the modified SWAT were better than those from the original SWAT, which did not follow the trend of the observed values (Fig. A5). The original SWAT simulated aboveground woody biomass hybrid poplar with populations of 17 and 278 trees/100 m^2 were unsatisfactory. P$_{\mathrm{BIAS}}$ values were −59% (17 trees/100 m^2) and −53% (278 trees/100 m^2), representing overestimated model simulation (Fig. A5). NSE (R^2) values for modeled aboveground woody biomass of hybrid poplar with populations of 17 and 278 trees/100 m^2 were 0.32 (0.78) and 0.29 (0.93), respectively. Projected woody biomass by the modified SWAT model was improved relative to simulations by the original SWAT, FOREST, and modified FOREST models (Table 7). Observed mean annual biomass increment (MABI) of 5-year old 69 trees/100 m^2 hybrid poplar was 7.6 Mg/ha/yr (Isebrands et al., 1979) (Table 7). Simulated values by FOREST, SWAT, and the modified SWAT models were 42% higher (Ek and Dawson, 1976a; b), 34% higher, and 4% lower than the observed value, respectively (Table 7). Additionally, the observed MABI value of 10-year old 17 trees/100 m^2 hybrid poplar was 10.4 Mg/ha/yr (Hansen, 1983) (Table 7). Projected values by the FOREST, modified FOREST, SWAT, and modified SWAT models were 96% higher (Ek and Dawson, 1976a; b), 81% higher (Meldahl, 1979), 86% lower, and 12% lower than the observed value, respectively (Table 7). Observed MABI value of 9-year old 8 trees/100 m^2 hybrid poplar was 6.2 Mg/ha/yr (Hansen, 1983) (Table 7). Modeled values by the FOREST, SWAT, and modified SWAT were 182% higher, 76% lower (Ek and Dawson, 1976a; b), and 19%

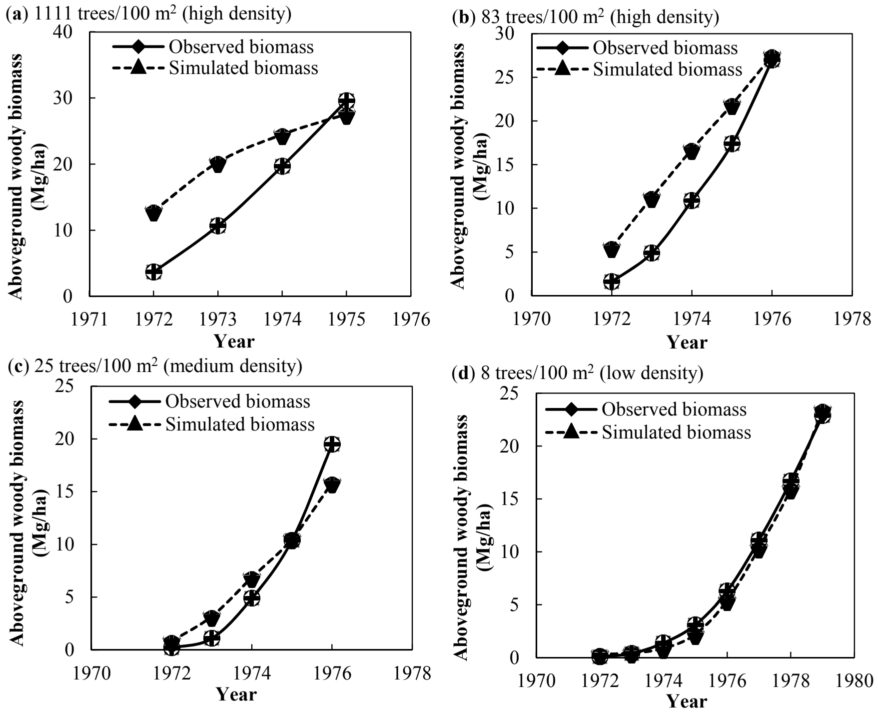

Fig. 6. Yearly observed and calibrated aboveground woody biomass of hybrid poplar with populations of 1111 (a), 83 (b), 25 (c) and 8 (d) trees/100 m² for the modified SWAT during validation. Aboveground woody biomass of hybrid poplar used for model validation includes stem and branch biomass.

higher than the observed value, respectively (Table 7).

In the original SWAT, tree density was governed using BLAI rather than a LAI factor that could represent the changes of seasonal LAI with different densities. Fraction of tree biomass converted to residue during the winter (BIO_LEAF) was invariable in the original SWAT. The original SWAT had difficulty in simulating how LAI increases to the maximum LAI, and thus could not accurately simulate biomass yields for juvenile hybrid poplar trees. Biomass yield simulation from FOREST and modified FOREST was based on estimated tree height, diameter and survival, which were higher than the observed values; thus, projected biomass was much higher than the observed biomass (Ek and Dawson, 1976a; b). Biomass yield simulation in SWAT was assumed proportional to the radiant energy absorbed by the plant canopy in an energy conversion model, and accurate biomass simulation was based on accurate LAI simulation (Arnold et al., 2012). The modified SWAT improved LAI simulation and thus improved biomass yield simulation for *Populus* trees (Guo et al., 2015), especially for *Populus* tree growth under SRIC systems, which usually reached maturity in several years. FOREST, modified FOREST, and SWAT could reasonably simulate biomass yield for mature trees. Modified SWAT could simulate acceptable LAI and biomass yield results for both juvenile and mature trees, and a further evaluation of its performance in simulating biomass yield for older stands, and stands with various populations and from various soils is needed.

Only three or four yearly/seasonal data observations were available for some tree populations. More continuous *Populus* growth, hydrology and water quality field data have the potential to improve determination of values and ranges for tree growth parameters in process based models and thus improve biomass yields and water quantity and quality response modeling of short rotation woody crops. Additionally, the current SWAT outputs only include plant total biomass, but aboveground woody biomass (stem and branch) is used as biofeedstock. Thus, it is desirable to improve the model to include root biomass, aboveground biomass and aboveground woody biomass in model outputs.

4. Conclusions

Populus has the potential to provide large quantities of biofeedstock for energy production, and it is important to quantify water quantity and water quality responses to *Populus* growth when it is planted in

Table 7
Comparison of projected and observed mean annual biomass increment (MABI) of 5-, 9- and 10-year-old short rotation intensively cultured hybrid poplar grown with various populations in Wisconsin (number in parentheses represents rate of increase/decrease of simulated results to related observed results).

Age (yr)	Spacing (m × m)	Population (trees/100 m²)	Observed MABI (Mg/ha)	Modeled MABI (Mg/ha)			
				Modified SWAT	SWAT	FOREST	Modified FOREST
5	1.2 × 1.2	69	7.6[a]	7.3[b] (−4%)	10.2[b] (34%)	10.8[c,d] (42%)	–
10	2.4 × 2.4	17	10.4[e]	9.2[b] (−12%)	1.5[b] (−86%)	20.4[c,d] (96%)	18.8[f] (81%)
9	3.6 × 3.6	8	6.2[e]	7.4[b] (19%)	1.51[b] (−76%)	17.5[c,d] (182%)	–

[a] (Isebrands et al., 1979).
[b] Present study.
[c] (Ek and Dawson, 1976a).
[d] (Ek and Dawson, 1976b).
[e] (Hansen, 1983).
[f] (Meldahl, 1979).

large areas as a biomass feedstock. Tree growth algorithms and parameters were previously improved in ALMANAC and reasonably simulated LAI and biomass yield of juvenile and mature *Populus*. The functional components and parameters of *Populus* are also useful for SWAT. In this study, SWAT was modified and used to simulate *Populus* growth and its impacts on runoff, sediment and nitrate-N losses. Sensitivity analysis was used to determine ranges and values of growth parameters of *Populus*. The modified SWAT with tree growth modification was used to simulate LAI and biomass yield of hybrid poplar with various populations in Wisconsin, and biomass yield of cottonwood and runoff, sediment and nutrient loading to *cottonwood* growth in Mississippi for model calibration. The calibrated model was used to simulate LAI and biomass yield of hybrid poplar with other populations in Wisconsin for model validation.

Populus biomass yield was sensitive to 10 of 35 plant growth parameters: BIO_E, T_OPT, T_BASE, EXT_COEF, TREED, MAT_YRS, and other leaf area development parameters (ALAI_MIN, BLAI, LAIMX2, and FRGRW2) in the SWAT plant dataset. The results of sensitivity analysis can provide guidance for determination of values or potential ranges for parameters and model calibration.

Modeled aboveground woody biomass and LAI values from the modified SWAT for hybrid poplar in Wisconsin were satisfactory (P_{BIAS}: 57 - 7%, NSE: 0.94–0.99, and R^2: 0.74–0.99). Performance of aboveground woody biomass simulation from the modified SWAT was superior to SWAT, FOREST, and modified FOREST models. FOREST, modified FOREST, and SWAT could reasonably simulate biomass yield for mature trees, and modified SWAT could accurately simulate LAI and biomass yield results for both juvenile and mature trees.

Additionally, modeled aboveground biomass, seasonal mean runoff, seasonal mean sediment, seasonal mean nitrate-N in runoff and seasonal total nitrate-N in runoff results from the modified SWAT model for the cottonwood site in Mississippi were good (P_{BIAS}: 39 - 11%, NSE: 0.86–0.99, and R^2: 0.93–0.99).

Thus, tree growth algorithms and parameters added in the modified SWAT and related changes in source code were acceptable. Values and potential ranges for hybrid poplar and cottonwood growth parameters were reasonable. The modified SWAT model can be used for biofeedstock production modeling for *Populus* (before and after maturity), and hydrologic and water quality response to its production at landscape scales. The improved algorithms and parameters for tree growth, and values and ranges for *Populus* should also be useful for other process based models, such as EPIC and APEX.

More continuous *Populus* growth, hydrology and water quality field data at monthly/seasonal levels have the potential to improve tree growth simulation in process based models. Incorporating root biomass, aboveground biomass and aboveground woody biomass in model outputs could enable simulation results to be more usable for biofeedstock study. In further study, it is also important to evaluate the performance of modified SWAT in simulating biomass yield, water quantity and quality impacts of older stands, stands in various soils, and with different densities.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envsoft.2018.08.030.

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