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# Functional Approach to Simulating Short-Rotation Woody Crops in Process-Based Models

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**Abstract** Short-rotation woody crops (SRWCs) such as *Populus* have great potential as biofuel feedstocks. Biomass yields and yield stability at potential sites are important considerations when SRWCs are widely planted. The process-based, daily time-step simulation model Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMANAC) offers promise as a useful tool to evaluate tree growth over large ranges of conditions. The objective of this study was to develop algorithms and growth parameters of hybrid poplar 'Tristis #1' (*Populus balsamifera* L. × *Populus tristis* Fisch) and eastern cottonwood (*Populus deltoides* Bartr.) in ALMANAC and to improve simulation of leaf area index (LAI) and plant biomass as well as biomass partitioning. ALMANAC with the improved algorithms for LAI and weight of falling leaves was applied to hybrid poplar plots in Wisconsin and cottonwood plots in Mississippi, and the modeled biomass yield and LAI were compared with measured data to modify and evaluate the location-specific ALMANAC models. Improved algorithms for LAI and biomass simulation and suggested values and potential parameter ranges for hybrid poplar and cottonwood were reasonable (Nash-Sutcliffe model efficiency (NSE) 0.81~0.99 and $R^2$ 0.76~0.99). ALMANAC with modified algorithms and parameters for *Populus* growth realistically simulated LAI, aboveground woody biomass, and root biomass of *Populus*. Thus, this model can be used for biofeedstock production modeling for *Populus*. The improved algorithms of LAI and biomass simulation for tree growth should also be useful for other process-based models, such as Soil and Water Assessment Tool (SWAT), Environmental Policy Integrated Climate (EPIC), and Agricultural Policy/Environmental eXtender (APEX).

**Keywords** Bioenergy · Short-rotation woody crops · Hybrid poplar · Cottonwood · Process-based models · Biofuel production modeling

## Introduction

Increasing energy demand and high sustained oil prices have encouraged the use of alternative forms of energy. The majority of biofuel production in the USA comes from sugar-rich maize (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr) oil. However, with the combination of a global increasing demand for renewable energy and food, the problems of food-fuel competition for land, higher food prices [1], and lower food production [2] will be created. Thus, beneficial biofuels should provide sustainable biofeedstocks that neither compete with food crops nor cause clearing of native forests. Non-food bioenergy crops—crop residues [3–7], cellulosic perennial crops (e.g., miscanthus (*Miscanthus×giganteus*), switchgrass

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(*Panicum virgatum* L.), mixed grasses) [8–16], and woody biomass crops (e.g., *Populus*)—offer great potential [17].

Short-rotation intensive culture of trees is considered a promising way to increase wood biomass productivity [18]. Dry matter production of wood plus bark in short-rotation hardwood plantations are up to 20,000 kg/ha/year, three to five times more than that for some natural stands [19]. Interest has increased in growing short-rotation plantations for energy production, since the oil embargo in 1973 [20]. The *Populus* genus is highly productive under short-rotation intensive culture system and is a good raw material for reconstituted forest products, due to its genetic diversity, rapid growth, vegetative propagation ease, and coppice regeneration [21].

Biomass productivity may increase with narrower tree spacing under short-rotation intensive culture system. Strong and Hansen [22] concluded that biomass differences related to spacing were minor in hybrid poplar plantations with 18 clone/spacing combinations for up to 16-year growth periods in northern Wisconsin. Productivity of hybrid poplar was mainly influenced by clone, irrigation, and disease. Similarly, Cannell and Smith [23] showed that close spacing was not essential for high biomass yield of hybrid poplar. However, tree spacing can affect time to canopy closure and the time needed to achieve maximum mean annual biomass increment (MABI). Hybrid poplar trees with wide tree spacing have longer rotations and more flexible harvest scheduling as well as lower costs [22, 23].

Prediction of *Populus* growth is critical for managers and policy makers to establish and manage short-rotation woody crops (SRWCs) and to obtain high yields. Some researchers studied simulation of hybrid poplar growth using tree growth models. For instance, Ek [24] used a model for regression estimation of branch weights of *Populus* which was found to be more precise than the models based on branch diameter. An individual-tree-based stand simulation model, FOREST, was used to simulate the periodic growth of hybrid poplar and showed that plot design, establishment techniques, cultural and environmental factors, measurement procedures, and model limitation can explain differences between the projected and observed harvest [25]. Meldahl [26] modified the FOREST model to simulate biomass yields of hybrid poplar and reduce the differences between projected and observed values. Moreover, Landsberg and Wright [27] simulated annual biomass production of two hybrid *Populus* clones in two locations using an energy conversion which assumes that plant biomass is proportional to the radiant energy absorbed by the canopy. Use of a radiant energy equation, also used in the Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMANAC) models as described below, resulted in better simulation performance of *Populus* biomass yields than other simulations based on tree branch weight or stand [27].

The ALMANAC model [28] is a process-based, daily time-step simulation model that has been parameterized and validated for a wide range of crop (corn and soybean), grass (switchgrass, miscanthus) and northern tree species [29] (lodgepole pine (*Pinus contorta* Douglas ex Loudon), white spruce (*Picea glauca* var. *glauca*), black spruce (*Picea mariana*), and trembling aspen (*Populus tremuloides* Michx.)). The model uses readily available USDA-NRCS soils data and readily available daily temperature and rainfall data. ALMANAC plant growth simulation processes include light interception, dry matter production, and biomass partitioned into plants [28, 30]. Biomass is calculated based on light interception and species-specific radiant use efficiency (RUE), which is the amount of dry biomass produced per unit of intercepted light [31, 32]. Three attributes useful for quantifying potential plant growth are as follows: RUE, LAI, and the light extinction coefficient ($k$) used to calculate the fraction of light intercepted by leaves [33].

Generally, RUE values for woody species are between 1.3 and 1.9 g/MJ intercepted photosynthetically active radiation (PAR) and for crops are between 2.2 and 3.5 g/MJ intercepted PAR [34]. Kiniry measured RUE values for eastern red cedar (*Juniperus virginiana*) (1.60 g/MJ intercepted PAR) and honey mesquite (*Prosopis glandulosa*) (1.61 g/MJ intercepted PAR) to allow better prediction of their growth in ALMANAC [33]. Mean RUE values were 1.5 for poplar in Wisconsin and Pennsylvania, USA [27], and RUE values were between 2.4 and 3.4 for intensively cultured poplar in Scotland [35]. The standard RUE values (g/MJ) should be multiplied by 10, to obtain the values (kg/ha)/(MJ/m$^2$) used in the ALMANAC and Soil and Water Assessment Tool (SWAT) [36].

Nineteen parameters for annual and long-term forest growth were incorporated and modified in the model to simulate successional forest regrowth after disturbance of forest ecosystems. Ranges of parameters were derived from scientific literature or yield tables. The ranges of RUE and $k$ values for mixed forest used in ALMANAC were determined as 15–20 and 0.5–0.55, respectively [37, 29]. However, research on biomass yields of trees simulated by ALMANAC is limited, since parameters and equations modified in the model are for mixed forest stands consisting of various woody species rather than a specific woody species [29].

Moreover, accurate LAI, biomass yield, and biomass partitioning simulation for *Populus* in ALMANAC has not been adequately developed, and it is important to quantify fast-growing tree growth accurately. In ALMANAC and SWAT, leaf area development, a sigmoid curve, is a function of the growing season for mature plants, during which mature plants can reach maximum LAI with the increase of heat units [36]. As LAI for juvenile trees cannot increase to maximum LAI, the leaf area algorithm used in the model was not suitable for juvenile tree growth simulation. Thus, ALMANAC can only simulate

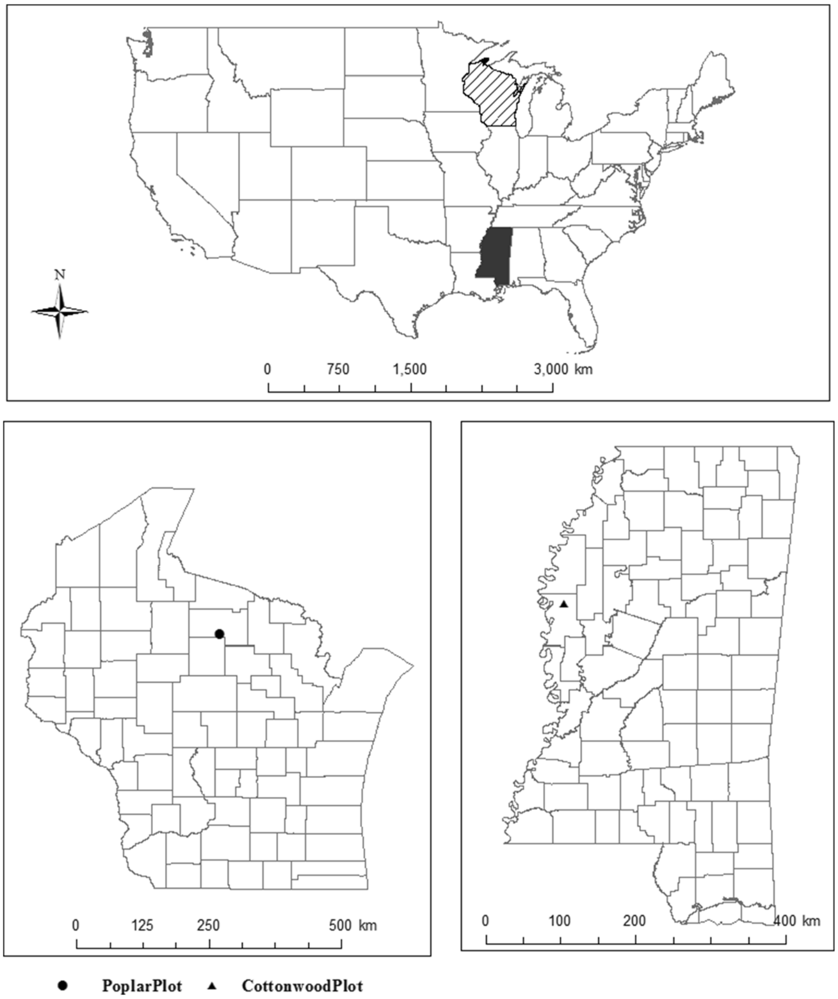


**Fig. 1** Location of hybrid poplar site at the USDA Forest Service Harshaw Experimental Farm near Rhinelander, WI, and cottonwood site at the Delta Research and Extension Center at Stoneville, MS

plant growth after plants reach maturity [36]. However, SRWCs were usually harvested once they reach maturity or even before maturity [21]. Thus, it is also important to improve the model to reasonably simulate tree growth from tree planting to maturity.

This work is a first effort to improve *Populus* growth algorithms and parameters in ALMANAC with published region-specific *Populus* growth data. The objectives of this study were to (1) develop algorithms and growth parameters of hybrid poplar 'Tristis #1' (*Populus balsamifera* L.

**Table 1** Data for hybrid poplar and cottonwood growth simulation by ALMANAC

| Plant | Data type | Source | Format | Date |
|---|---|---|---|---|
| Hybrid poplar | SSURGO | USDA Web Soil Survey | Polygon shapefile | |
| | Precipitation and temperature | NCDC | | 1970–1980 |
| | Annual aboveground woody biomass yield (metric ton (t)/ha) | Scientific literature[a] | | 1970–1980 |
| | Annual LAI | Scientific literature[a] | | 1970–1980 |
| Cottonwood | SSURGO | USDA Web Soil Survey | Polygon shapefile | |
| | Precipitation and temperature | NCDC | | 1995–1997 |
| | Annual aboveground biomass yield (t/ha) | Unpublished report[b] | | 1995–1997 |
| | Annual root biomass (t/ha) | Unpublished report[b] | | 1995–1997 |

*SSURGO*, Soil Survey Geographic Database, *USDA* US Department of Agriculture, *NCDC* National Climate Data Center

[a] Hansen [21]

[b] Pettry et al. (1997), unpublished annual progress report

**Table 2** Management operations for hybrid poplar site at the USDA Forest Service Harshaw Experimental Farm near Rhinelander, WI

| Plant | Date | Management operation | Rate (kg/ha) |
|---|---|---|---|
| Hybrid poplar | 30 May | Tillage, roto-tiller (mixing depth 5 mm, mixing efficiency 0.80) | |
| | 1 June | Planting | |
| | 1 June | Pesticide application (as linuron) | 2.2[a,b] |
| | 1 June | Nitrogen application (as anhydrous ammonia) | 200[a,b] |
| | 1 June | Phosphorus application (as elemental phosphorus) | 50[a,b] |
| | 31 Dec | The end of the operation scheduling for a year | |

[a] Ek and Dawson [40]

[b] Srinivasan and Cibin (2014), personal communication

× *Populus tristis* Fisch) and eastern cottonwood (*Populus deltoides* Bartr.) in ALMANAC and to improve simulation of leaf area and plant biomass as well as biomass partitioning, (2) use the modified model to simulate LAI and aboveground woody biomass of hybrid poplar in Wisconsin and aboveground woody biomass and root biomass of cottonwood in Mississippi, and (3) compare simulated LAI and biomass results from the modified model with observed values for verification of improved algorithms and growth parameters of *Populus*.

## Materials and Methods

### Hybrid Poplar Site in Northern Wisconsin and Cottonwood Site in Western Mississippi

This study was conducted using data in the literature from two study sites (Fig. 1). The poplar site was a short-rotation intensive culture plantation at the USDA Forest Service Harshaw Experimental Farm near Rhinelander, WI, USA (45.6° N, 89.5° W) [38, 39]. Hybrid poplar cuttings were planted in early June, 1970, on a prepared site [40]. The site was sowed to rye, plowed, and rototilled before planting [22]. The soil of the plantation is the Padus series, a silt loam, overlaying sand, and gravel at depths of 30 to 60 cm with slope reaching at most 1 %. The pH is from 6.7 to 7.0 [40]. The average growing season of hybrid poplar in this region is 120 days.

The cottonwood site was at the Delta Research and Extension Center at Stoneville, Mississippi, in the Tennessee Valley region [41], which was on agricultural land with a Bostket silt loam soil, a fine loamy, mixed, thermic Mollic Hapludalfs. The slope gradient is 0.2 %. Soil quality changes were determined based on soil physical characteristics measured at the site in 1995 (prior to tree establishment) and in 1997 (at the end of growing season) [42]. Cottonwood cuttings 20–30 cm long were planted with spacing of 1.2×3.6 m (population 23 trees/100 $m^2$) on 3 February, 1995 [43], and harvested during 1–20 November, 1997 (Pettry et al. 1997, unpublished annual progress report).

### ALMANAC Model Setup and Management Schedules

ALMANAC 2011 (Version 1.0.3 Beta 2) with Interface (Version 1.0.3) was used in this project. A new crop named "Poplar Tian Low" and "Cottonwood" were added to represent hybrid polar and cottonwood, respectively. Lat 45.6° and long 89.5°, and lat 33.34° and long 90.85° were used for the hybrid poplar and cottonwood sites, respectively. The fraction of total tree biomass partitioned to roots was assumed to be 0.5 for hybrid poplar [21] and 0.2 for cottonwood (Pettry et al. 1997, unpublished annual progress report). Table 1 describes the primary data required for ALMANAC model setup.

**Table 3** Management operations for cottonwood site at the Delta Research and Extension Center at Stoneville, MS

| Plant | Date | Management operation | Rate (kg/ha) |
|---|---|---|---|
| Cottonwood | 3 Feb | Tillage, roto-tiller (mixing depth 5 mm, mixing efficiency 0.80) | |
| | 3 Feb | Planting | |
| | 3 Feb | Pesticide application (as linuron) | 2.2[a,b] |
| | 1 June | Nitrogen application (as anhydrous ammonia) | 200[a,b] |
| | 1 June | Phosphorus application (as elemental phosphorus) | 30[a,b] |
| | 31 Dec | The end of the operation scheduling for a year | |

[a] Thornton et al. [43] and Joslin and Schoenholtz [41]

[b] Srinivasan and Cibin (2014), personal communication

**Table 4** Hybrid poplar and cottonwood growth data for model calibration and validation

| *Populus* | Population (trees/100 m$^{2)}$ | Density level | Outputs (annual aboveground woody biomass (AAWB), LAI, annual aboveground biomass (AAB), and root biomass (RB)) | Data usage |
|---|---|---|---|---|
| Hybrid poplar | 278 | High | LAI | Model calibration |
| | 278 | High | AAWB (t/ha) | |
| | 69 | Medium | AAWB (t/ha) | |
| | 17 | Low | LAI | |
| | 17 | Low | AAWB (t/ha) | |
| | 1111 | High | AAWB (t/ha) | Model validation |
| | 83 | High | LAI | |
| | 83 | High | AAWB (t/ha) | |
| | 25 | Medium | LAI | |
| | 25 | Medium | AAWB (t/ha) | |
| | 8 | Low | AAWB (t/ha) | |
| Cottonwood | 23 | Medium | AAB (t/ha) | |
| | 23 | Medium | RB (t/ha) | |

ALMANAC management includes planting and end of schedule dates, yearly tillage, pesticide, and nutrient application rates. Tables 2 and 3 represent management operations for hybrid poplar growth in 1970 and cottonwood growth in 1995. Fertilizer and auto irrigation were also added to these two location-specific models to ensure that *Populus* growth was not under water stress or nutrient stress. Nutrient application dates and rates for hybrid poplar growth from years 1971 to 1980 and cottonwood growth during years 1996 and 1997 were the same as nitrogen and phosphorus application in Tables 2 and 3, respectively. Hybrid poplar planting was on 22 May, 1970, and harvest was on 1 May, 1980. Cottonwood planting was on 3 February, 1995, and harvest was on 30 Nov, 1997.

## Algorithm and Parameter Changes in the Model

Deciduous tree LAI increases both within each growing season prior to late-season senescence and among years as the maximum seasonal LAI increases. The seasonal leaf area development curve in the model can be used in years prior to maturity year after adjusting each year's potential LAI. Published yearly LAI values for *Populus* trees with various planting densities ranged from 8 to 1111 trees/100 m$^2$ (Table 10 of Appendix). The increase in maximum seasonal LAI across years for *Populus* with various densities was similar to the equation of loss of leaf late in the season [44]. This served as the starting point to derive a new leaf development algorithm to simulate maximum seasonal LAI each year with various densities.

$$y_{\mathrm{yr}} = y_{\mathrm{yr}-1} * 10^{\log 10\left(\frac{\mathrm{yr}}{x_1}\right) * x_2} \tag{1}$$

where yr is the current growth year, $y_{\mathrm{yr}}$ is the LAI value for current year, $\mathrm{y}_{\mathrm{yr}-1}$ is the LAI value for previous year, $x_1$ is the number of years until maximum LAI is attained (CLAIYR), and $x_2$ is a new tree leaf factor (TreeD) in the LAI algorithm, representing how LAI increases to the maximum potential LAI (DMLA) with varying densities.

CLAIYR values for *Populus* trees with various densities were obtained from a previous study [21]. A specific density of *Populus* trees has an associated TreeD value representing its LAI development. Based on published LAI values for different years and CLAIYR values, TreeD in Eq. (1) was

**Table 5** Hybrid poplar tree growth parameters for various spacings for used in LAI simulation in the modified ALMANAC

| Population (trees/100 m$^2$) | Spacing (m×m) | DMLA (maximum LAI) in ALMANAC) | Observed DMLA | TreeD (LAI factor) | CLAIYR (year to attain maximum LAI) |
|---|---|---|---|---|---|
| 1111 | 0.3×0.3 | 9.5 | 8.6 | 0.5 | 6 |
| 278 | 0.6×0.6 | 9.5 | 8.6 | 0.75 | 6 |
| 83 | 1.1×1.1 | 9.5 | 8.6 | 1.5 | 6 |
| 69 | 1.2×1.2 | 9.5 | 8.6 | 2.5 | 6 |
| 25 | 2×2 | 9.5 | 8.6 | 3 | 6 |
| 17 | 2.4×2.4 | 9.5 | 8.6 | 2 | 7 |
| 8 | 3.6×3.6 | 9.5 | 8.6 | 4.5 | 9 |

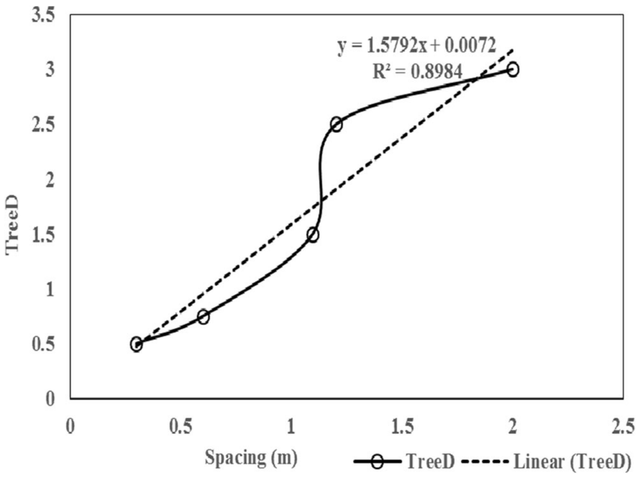


**Fig. 2** ALMANAC TreeD parameters for hybrid poplar trees with various spacings

calibrated manually for various populations to match observed values.

The management parameter "POPULATION" is the number of trees per 100 m$^2$. Previously, ALMANAC did not include a specific parameter for population effects on maximum seasonal LAI over years. In this new version, TreeD values in the crop database are used for different populations for *Populus* trees to calculate these seasonal maximums.

Total tree biomass consists of root biomass, senescent dropped leaf weight, and aboveground biomass (leaves, stems, and branches). To accurately simulate *Populus* tree biomass partitioning, the algorithm used for dropping leaves was improved (see details in the Appendix).

## Values and Ranges of Parameters Determined Before Model Calibration

Two-week moving average daily temperatures at the USDA Forest Service Harshaw Experimental Farm in Wisconsin and the Stoneville site in Mississippi were obtained using Matlab 2013 based on NOAA daily temperature data to determine base temperature (TG). The period of emergence was assumed from 1 to 20 April for hybrid poplar and 20 March to 10 April for cottonwood [45–47], which were day of year 90 to 110 and 78 to 98, respectively.

Values of potential heat unit (PHU) for hybrid poplar growth in Wisconsin and cottonwood growth in Mississippi were calculated based on accumulation of heat units during the growing season [48]. The growing season of hybrid poplar on the Harshaw experiment farm and cottonwood at the Stoneville site was assumed from 1 April to 11 October and from 20 March to 31 October, respectively [45–47] (see details in Appendix).

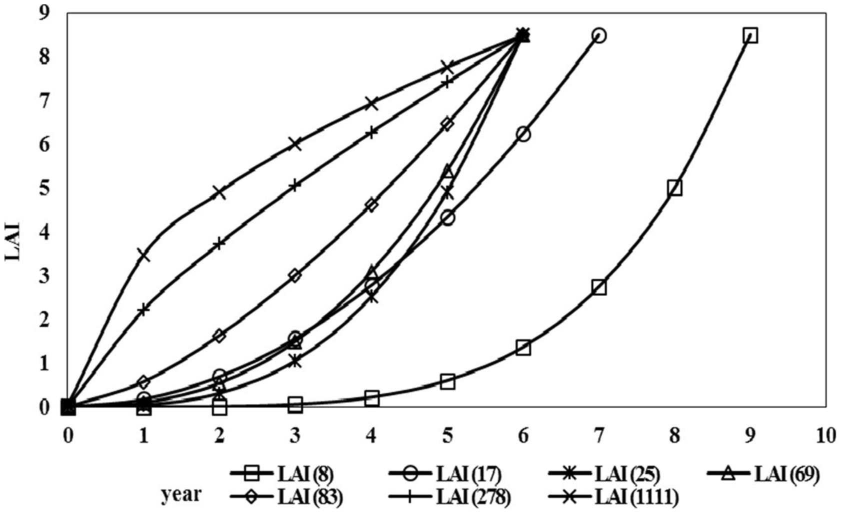
Values of hybrid poplar and cottonwood growth parameters maximum rooting depth (RDMX); rate of decline in RUE per unit increase in vapor pressure deficit (WAVP); plant nitrogen (N) at emergence (BN$_1$), 50 % maturity (BN$_2$), and maturity (BN$_3$); phosphorus fraction at emergence (BP$_1$), 50 % maturity (BP$_2$), and maturity (BP$_3$) [33, 29]; and harvest index (HI) for optimal growing conditions [36, 46] were derived from previous studies (see details in Appendix).

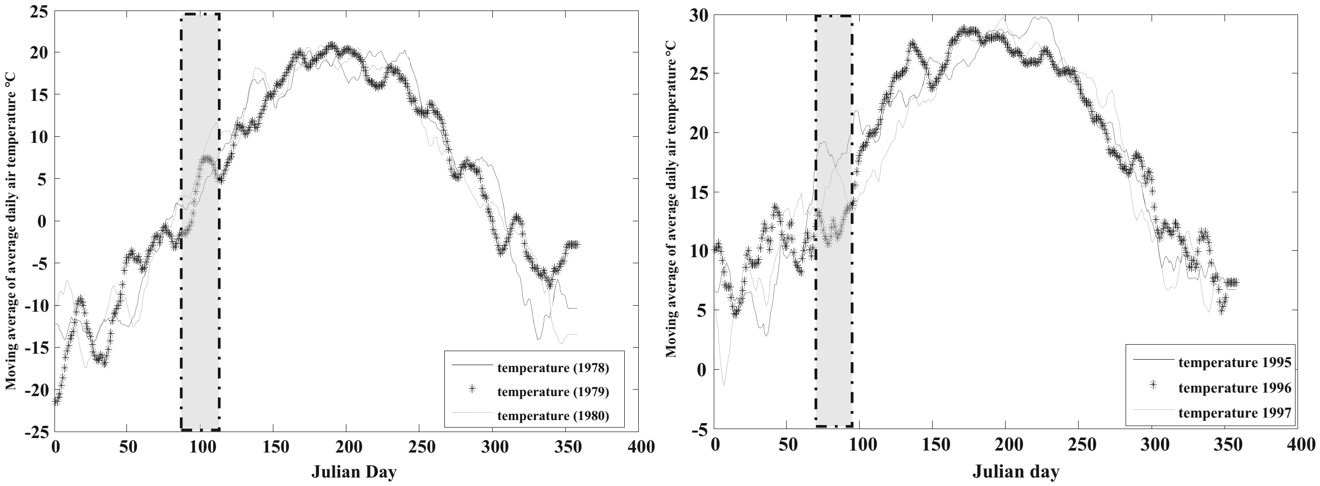
Values of plant maximum stomatal conductance (GSI) and maximum canopy height (HMX) for *Populus* growth simulation in the model were assumed before model calibration based on personal communication (Kiniry 2014) (see details in Appendix).

## ALMANAC Model Calibration and Parameterization

Previous hybrid poplar growth studies at the USDA Forest Service Harshaw Experimental Farm in Wisconsin [49, 21, 27, 50, 51] suggested values for RUE (called WA in the model), *k* (called EXTINC in the model), DMLA, two points on optimal leaf development curve parameters (DLAP1 and DLAP2), fraction of growing season when leaf area starts declining (DLAI), plant N fraction in harvested biomass

**Fig. 3** Simulated LAI curve for hybrid poplar trees with various populations (number in parentheses is population (trees/100 m$^2$) of hybrid poplar trees)





(a) Hybrid Poplar Site in Wisconsin (b) Cottonwood Site in Mississippi

**Fig. 4** Two-week moving average daily temperatures at Harshaw Experiment Farm in Wisconsin and at Stoneville Site in Mississippi (*gray bands* are periods of emergence). **a** Hybrid poplar site in Wisconsin. **b** Cottonwood site in Mississippi

(CNY), and plant P fraction in harvested biomass (CNP) (see details in Appendix), providing reasonable ranges of these tree growth parameters for model calibration. Ranges of PHU values were calculated before model calibration. The model was calibrated by changing these *Populus* growth parameters manually to obtain a good fit with published hybrid poplar LAI and aboveground biomass values. Values of WA, EXTINC, DMLA, DLAP1 and DLAP2, DLAI, CNY, and PHU were determined after model calibration.

The LAI and aboveground woody biomass data of hybrid poplar with various spacings and aboveground biomass and root biomass of cottonwood with medium density used for model calibration and validation are summarized in Table 4.

### Validation of the Modified ALMANAC Model

The methods used for verifying the model performance [52] include percent bias/percent error ($P_{\mathrm{BIAS}}$ [%]), Nash-Sutcliffe model efficiency (NSE) coefficient , and coefficient of determination ($R^2$). Value of $P_{\mathrm{BIAS}}$ [53] is a measure of the average tendency of the simulated data to be larger or smaller than the measured data. The value of 0.0 is the optimal value of $P_{\mathrm{BIAS}}$. Negative values represent overestimation bias, and positive values represent underestimation bias. The NSE [54] describes how well measured versus simulated data plots match the 1:1 line. The NSE value ranges from $-\infty$ to 1, and the optimal value is 1. We assumed that a NSE value of greater than 0.5 meant that model performance is satisfactory [55]. Values of $0.36 \leq \mathrm{NSE} \leq 0.72$ and $\mathrm{NSE} \geq 0.75$ also have been considered satisfactory and good simulated results, respectively [56, 57]. The $R^2$ value indicates the strength of the linear relationship between the measured and simulated data. We assumed that an $R^2$ value of greater than 0.5 indicated reasonable model performance [55].

## Results and Discussion

### Algorithm and Parameter Changes in the Model

Leaf area cover, as defined by leaf area index (LAI), is a driving variable determining amount of light intercepted and, thus, biomass via the RUE approach. Simulated LAI also drives potential transpiration, an important component of the total evapotranspiration of the system. Deciduous tree LAI increases both within each growing season prior to late-season senescence and among years. Values for LAI also vary with planting density of trees. Within each growing season, LAI decreases late in the season with leaf senescence. Tree spacing was converted to population (Table 5). TreeD, CLAI YR, observed DMLA, and DMLA for various spacings used in LAI simulation in the modified ALMANAC are shown in Table 5. For high-density (population of 1111, 278 or 83 trees/ 100 m$^2$) and medium-density (population of 69 or 25 trees/

**Table 6** Potential heat units for *Populus* during each growing season of different years

| Plant | Year | PHU |
|---|---|---|
| Hybrid poplar | 1974 | 1670 |
| | 1975 | 1999 |
| | 1976 | 2047 |
| | 1977 | 2149 |
| | 1978 | 1956 |
| | 1979 | 1893 |
| | 1980 | 1986 |
| Cottonwood | 1995 | 2899 |
| | 1996 | 2818 |
| | 1997 | 2421 |

**Table 7** Suggested values and potential parameter ranges for hybrid poplar and cottonwood compared to current parameters for *Populus* in ALMANAC crop database

| Parameter Acronym in ALMANAC | Parameter definition | Hybrid poplar ‘Tristis #1' *Populus balsamifera* L. × *Populus tristis* Fisch (HYPT) | |
|---|---|---|---|
| | | Suggested value | Range |
| TG$^{a}$ [PHU]$^{a,c}$ | Base temperature (°C) Heat units to maturity | 4 [1750] | 0–6 [2150–1500] |
| TB$^{b}$ | Optimal temperature (°C) | 25 | 25–30 |
| WA$^{c,d}$ | Radiation use Efficiency in ambient $CO_2$ (kg/ha)/(MJ/m$^2$) | 20 | 20–35 |
| EXTINC$^{c,d}$ | Light extinction coefficient | 0.30 | 0.20–0.60 |
| DMLA$^{c,e,f}$ | Maximum LAI | 9.50 | 5.00–9.50 |
| DLAI$^{c,e,f}$ | Point in growing season when LAI declines | 0.99 | 0.99 |
| TREED$^{c,e}$ | Tree leaf area decline factor | 0.500–4.500 | 0.500–4.500 |
| BP$_1^{g,h}$ | Plant P fraction at emergence (whole plant) | Existing value | Existing value |
| GSI$^{b}$ | Maximum stomatal conductance | 0.0070 | 0.0040–0.0070 |
| HMX$^{b}$ | Maximum canopy height | Existing value | 7.00–15.00 |
| BN$_1^{g,h}$ | Plant N fraction at emergence (whole plant) | Existing value | Existing value |
| BN$_3^{g,h}$ | Plant N fraction at maturity (whole plant) | Existing value | Existing value |
| BN$_2^{g,h}$ | Plant N fraction at 50 % maturity (whole plant) | Existing value | Existing value |
| RDMX$^{g,h}$ | Maximum rooting depth | Existing value | Existing value |
| CNY$^{c,i,j}$ | Plant N fraction in harvested biomass | 0.0005 | 0.0005–0.0015 |
| CPY$^{c,k}$ | Plant P fraction in harvested biomass | 0.0002 | 0.0002–0.0003 |
| BP$_2^{g,h}$ | Plant P fraction at 50 % maturity (whole plant) | Existing value | Existing value |
| BP$_3^{g,h}$ | Plant P fraction at maturity (whole plant) | Existing value | Existing value |
| WAVP$^{g,h}$ | Rate of decline in RUE per unit increase in vapor pressure deficit | Existing value | Existing value |
| CHTYR$^{e,f}$ | Number of years required for tree species to reach full development (years) | 6–9 | 6–9 |
| HI$^{l,m}$ | Harvest index for optimal growing conditions | 0.65 | 0.45–0.70 |
| Optimal leaf development curve parameters | | | |
| DLAP1$^{c,e,f}$ | Fraction of growing season coinciding with first point | 0.05 | 0.05–0.07 |
| | Fraction of DMLA corresponding to first point | 0.05 | 0.05–0.30 |
| DLAP2$^{c,e,f}$ | Fraction of growing season coinciding with second point | 0.40 | 0.40–0.45 |
| | Fraction of DMLA corresponding to second point | 0.95 | 0.95–0.98 |

| Parameter Acronym in ALMANAC | Eastern cottonwood *Populus deltoides* Bartr. (POEC) | | *Populus* (POPL) |
|---|---|---|---|
| | Suggested value | Range | Database value |
| TG$^{a}$ [PHU]$^{a,c}$ | 8 [2818] | 7–15 [2900–2200] | 10– |
| TB$^{b}$ | 25 | 25–30 | 30 |
| WA$^{c,d}$ | 41 | 30–58 | 30 |
| EXTINC$^{c,d}$ | 0.60 | 0.20–0.60 | 0.45 |
| DMLA$^{c,e,f}$ | 9.50 | 5.00–9.50 | 5.00 |
| DLAI$^{c,e,f}$ | 0.99 | 0.99 | 0.99 |
| TREED$^{c,e}$ | 0.500–4.500 | 0.500–4.500 | |
| BP$_1^{g,h}$ | Existing value | Existing value | 0.0007 |
| GSI$^{b}$ | 0.0070 | 0.0040–0.0070 | 0.0040 |
| HMX$^{b}$ | 10.00 | 10.00–15.00 | 7.50 |
| BN$_1^{g,h}$ | Existing value | Existing value | 0.0060 |
| BN$_3^{g,h}$ | Existing value | Existing value | 0.0015 |
| BN$_2^{g,h}$ | Existing value | Existing value | 0.0020 |
| RDMX$^{g,h}$ | Existing value | Existing value | 3.50 |
| CNY$^{c,i,j}$ | 0.0005 | 0.0005–0.0015 | 0.0015 |
| CPY$^{c,k}$ | 0.0002 | 0.0002–0.0003 | 0.0003 |
| BP$_2^{g,h}$ | Existing value | Existing value | 0.0004 |
| BP$_3^{g,h}$ | Existing value | Existing value | 0.0003 |
| WAVP$^{g,h}$ | Existing value | Existing value | 8.00 |

**Table 7** (continued)

| Parameter Acronym in ALMANAC | Eastern cottonwood *Populus deltoides* Bartr. (POEC) | | *Populus* (POPL) |
|---|---|---|---|
| | Suggested value | Range | Database value |
| CHTYR[e,f] | 6–9 | 6–9 | 10 |
| HI[l,m] | 0.60 | 0.40–0.65 | 0.76 |
| Optimal leaf development curve parameters | | | |
| DLAP1[c,e,f] | 0.05 | 0.05–0.07 | 0.05 |
| | 0.05 | 0.05–0.30 | 0.05 |
| DLAP2[c,e,f] | 0.40 | 0.40–0.45 | 0.40 |
| | 0.95 | 0.95–0.98 | 0.95 |

[a] Maximum and minimum daily temperature from NOAA

[b] Assumed

[c] Modified parameter from hybrid poplar growth simulation

[d] Landsberg and Wright [27]

[e] Hansen [21]

[f] Zavitkovski [51]

[g] Kiniry [32]

[h] MacDonald et al. [37]

[i] Black et al. [49]

[j] McLaughlin et al. [50]

[k] Kiniry (2014), personal communication

[l] Michael et al. [47]

[m] Arnold et al. [36]

100 m$^2$) hybrid poplar trees, a shorter time (6 years) is needed to attain DMLA. For low-density (population of 17 or 8 trees/100 m$^2$) hybrid poplar trees, a longer time (7 or 9 years) is needed to attain DMLA.

Based on TreeD and tree spacing values (Table 5) for high- and medium-density hybrid poplar trees (Fig. 2), TreeD is linearly related to tree spacing (Eq. (2)). Equation (2) was assumed suitable for short-rotation *Populus* trees which can attain DMLA in 6 years. For *Populus* trees attaining DMLA in 6 years, the higher tree spacing (smaller tree population) is associated with higher TreeD values. For *Populus* trees which attain DMLA in 7 to 9 years, the TreeD values can be found in Table 5.

$$y = 1.579 * x + 0.007, \quad R^2 = 0.898 \qquad (2)$$

where $y$ is the TreeD parameter and $x$ is the tree planting spacing (m).

Maximum seasonal LAI values of hybrid poplar with different populations calculated by Eq. (1) are shown in Fig. 3. For high-density hybrid poplar trees, LAI can increase significantly at the beginning (years 1 to 3) and attain maximum LAI in a shorter time (6 years). For low-density hybrid poplar trees, LAI increases slowly at the beginning (years 1 to 3) and attains maximum LAI at a later time (7 or 9 years). Thus, tree spacing can affect time to canopy closure, and wide tree spacing allows longer rotations of hybrid poplar if canopy closure by harvest year is desirable. This is consistent with results of Strong and Hansen [22].

The algorithm used for dropping leaves was improved to more accurately simulate weight of dropping leaves.

$$y = x_1 * \left( 0.4 - 0.3 * \frac{\mathrm{yr} - 1}{x_2 - 1} \right) \qquad (3)$$

where $y$ is the weight of dropping leaves, yr is the current growth year, $x_1$ is the aboveground biomass, and $x_2$ is the number of years to maximum height and maximum LAI of trees (CHTYR).

## Values and Ranges of Parameters Determined Before Model Calibration

Two-week moving average daily temperature plots of hybrid poplar and cottonwood growth are shown in Fig. 4. The gray bands were the period of emergence for hybrid poplar (Fig. 4a) and cottonwood (Fig. 4b) growth, respectively. Temperatures in the gray bands were the ranges of TG for *Populus* growth. TG was chosen as 4 °Cfor hybrid poplar (within the expected range 0–6 °C (Srinivasan R 2014, personal

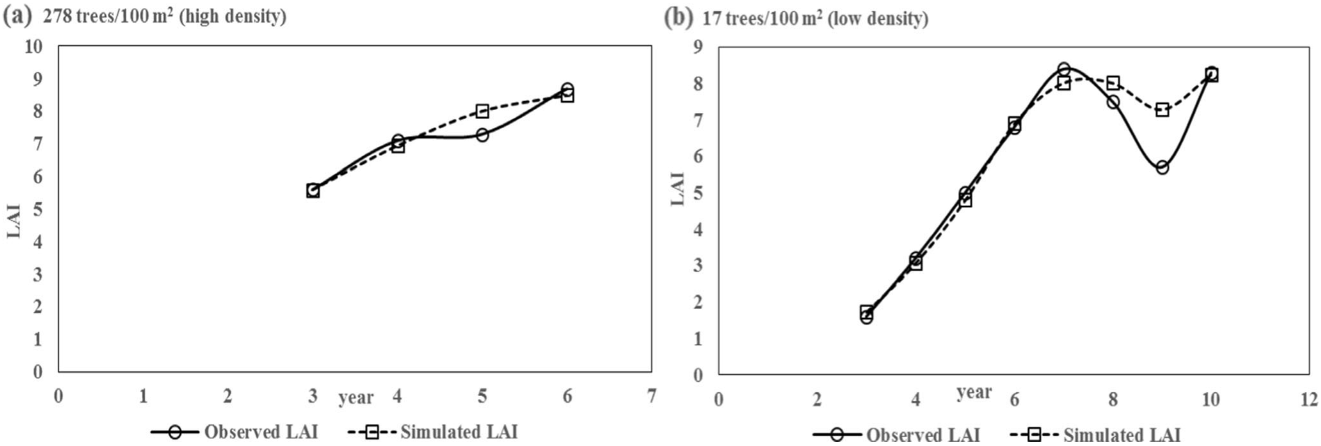


**Fig. 5** Yearly observed and calibrated ALMANAC (modified) simulated LAI during calibration of hybrid poplar with populations of 278 (**a**) and 17 (**b**) trees/100 m$^2$

communication)) and 8 °C for cottonwood. The generic optimal temperature for warm season plants, 25 °C, was chosen for optimal temperature (TB) of hybrid poplar and cottonwood growth in this study [36].

The PHU values were calculated during each growing season from 1974 to 1980 for hybrid poplar and from 1995 to 1997 for cottonwood (Table 6). The range of possible values for PHU is 1670–2150 for hybrid poplar in Wisconsin and 2421–2899 for cottonwood in Mississippi.

Assumed values and ranges of RDMX, WAVP, $BN_1$, $BN_2$, $BN_3$, $BP_1$, $BP_2$, $BP_3$, HI, GSI, and HMX for hybrid poplar and cottonwood growth are summarized in Table 7.

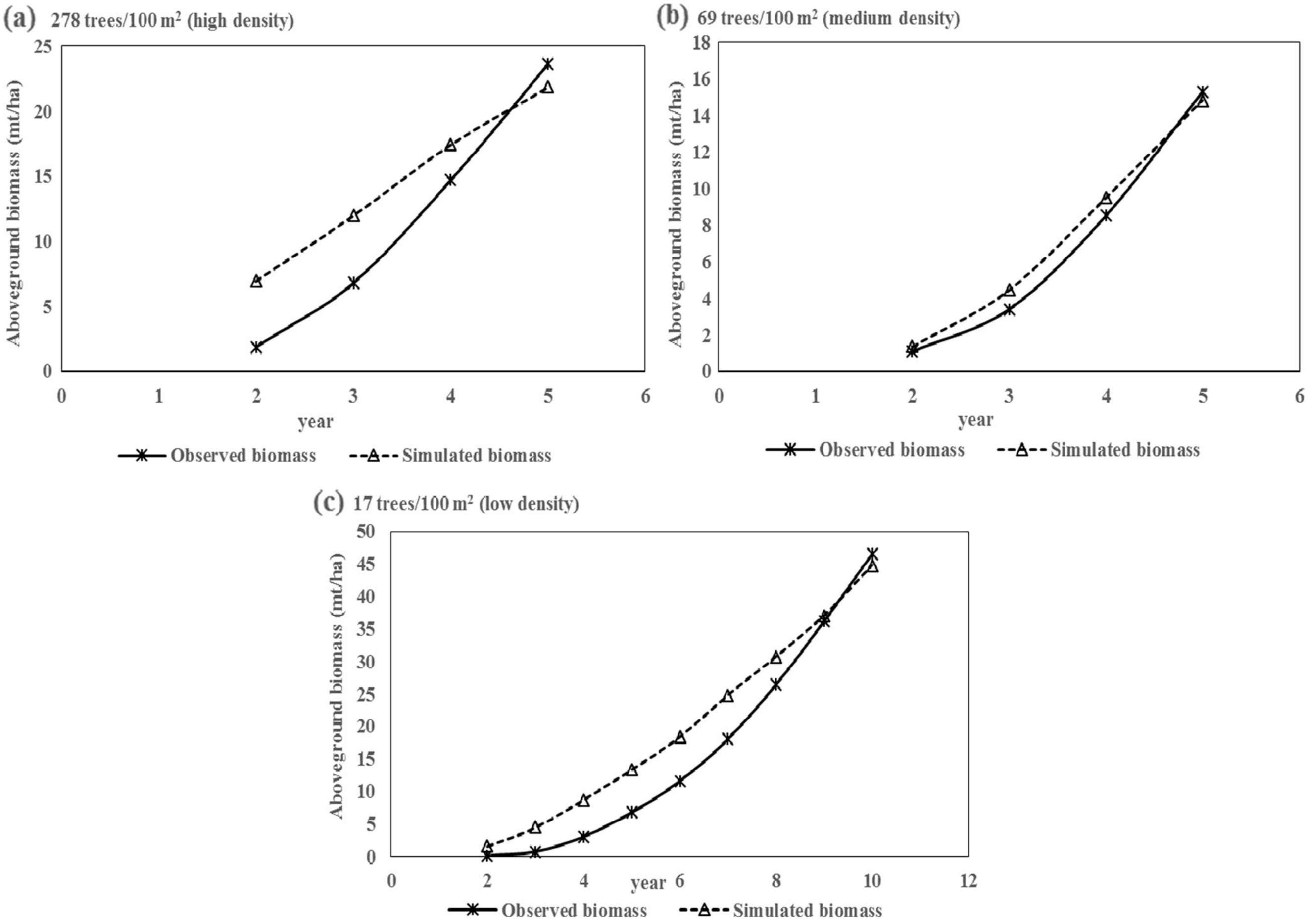


**Fig. 6** Yearly observed and calibrated ALMANAC (modified) simulated aboveground woody biomass during calibration of hybrid poplar with populations of 278 (**a**), 69 (**b**), and 17 (**c**) trees/100 m$^2$

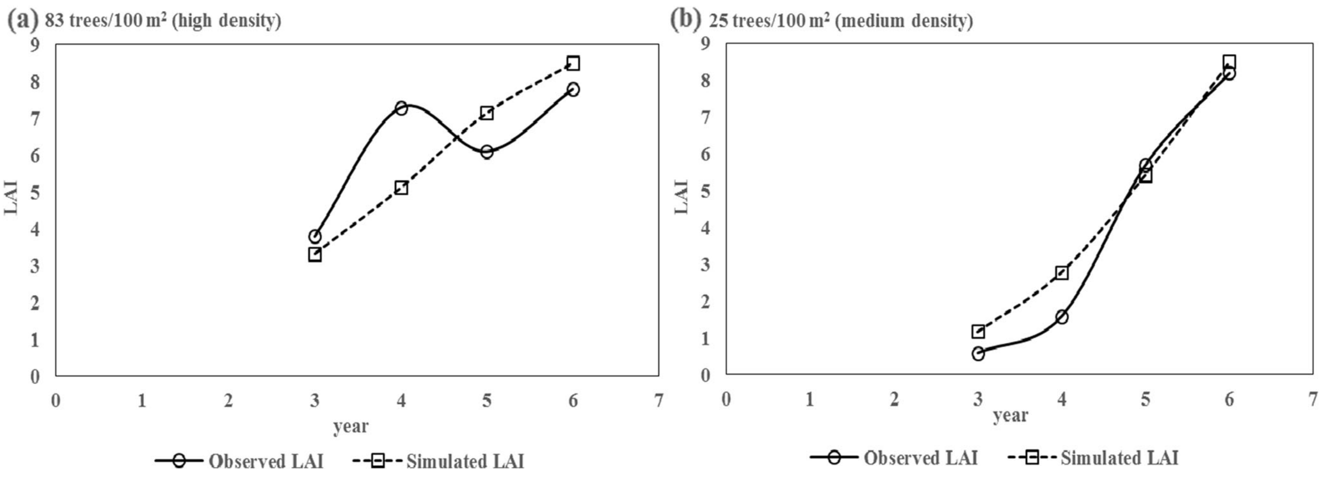


**Fig. 7** Yearly observed and calibrated ALMANAC (modified) simulated LAI during validation of hybrid poplar with populations of 83 (**a**) and 25 (**b**) trees/100 m$^2$

## ALMANAC Model Calibration for Hybrid Poplar Growth in Wisconsin

Calibrated annual LAI values by ALMANAC were compared with published values for hybrid poplar with populations of 278 (high density) and 17 (low density) trees/100 m$^2$ (Fig. 5). Calibrated annual aboveground woody biomass values were compared with published values for hybrid poplar with populations of 278, 69 (medium density), and 17 trees/100 m$^2$ (Fig. 6).

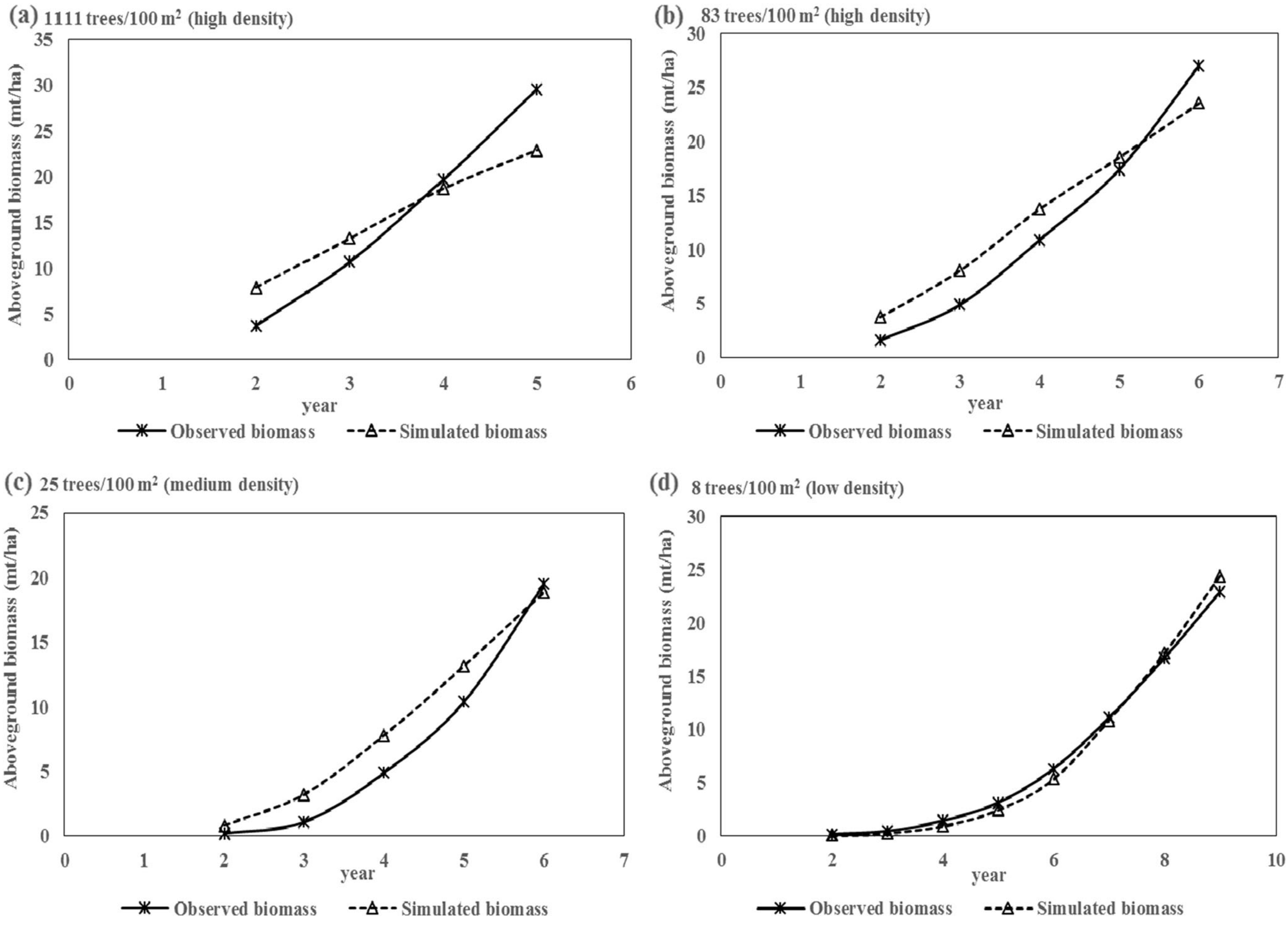


**Fig. 8** Yearly observed and calibrated ALMANAC (modified) simulated aboveground woody biomass during validation of hybrid poplar with populations of 1111 (**a**), 83 (**b**), 25 (**c**), and 8 (**d**) trees/100 m$^2$

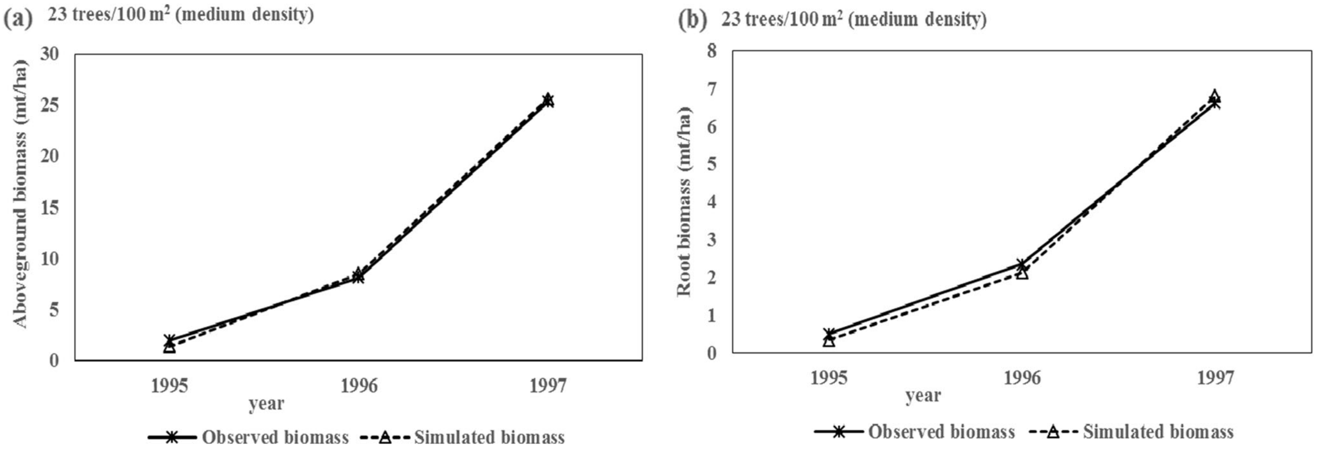


**Fig. 9** Yearly observed and calibrated ALMANAC (modified) simulated aboveground biomass (**a**) and root biomass (**b**) during validation of cottonwood with a population of 23 trees/100 m$^2$

Simulated annual LAI of hybrid poplar with populations of 278 and 17 trees/100 m$^2$ had a reasonable good match with observed values, except that the simulated LAI value at year 9 (population of 17 trees/100 m$^2$) was slightly higher than the observed value (Fig. 5).

Projected annual aboveground woody biomass of hybrid poplar with populations of 278, 69, and 17 trees/100 m$^2$ fit the observed values reasonably well, except that simulated annual aboveground woody biomass values at years 2 and 3 (population of 278 trees/100 m$^2$) were higher than the observed values (Fig. 6). Simulated annual aboveground woody biomass values at years 2, 3, and 4 (population of 17 trees/100 m$^2$) were higher than the observed values.

### Suggested Values and Potential Parameter Range for Hybrid Poplar and Cottonwood in ALMANAC Model

ALMANAC realistically simulated annual LAI and aboveground woody biomass yield of hybrid poplar with various spacings. Suggested values and potential parameter ranges for hybrid poplar and cottonwood were determined (Table 7). Existing values or ranges of growth parameters used in ALMANAC are globally approximated, since it is time-consuming and difficult to obtain growth data in detail for each species. The existing values or ranges can be adjusted in specific regions before being used for plant growth simulation.

### Modified ALMANAC Model Validation for Hybrid Poplar and Cottonwood Growth

Comparisons of annual LAI values modeled by the modified ALMANAC with published values for hybrid poplar with populations of 83 (high density) and 25 (medium density) trees/100 m$^2$ are shown in Fig. 7. Comparisons of annual aboveground woody biomass modeled values with published values for hybrid poplar with populations of 1111 (high density), 83, 25, and 8 (low density) trees/100 m$^2$ are shown in Fig. 8. Comparisons of modeled annual aboveground biomass and root biomass with published values for cottonwood with a population of 23 trees/100 m$^2$ (medium density) are shown in Fig. 9. The modified model was validated based on the percent

**Table 8** Evaluation of model outputs with various populations for the modified ALMANAC

| Plant | Population (trees/100 m$^{2)}$ | Density level | Outputs Aboveground woody biomass (AWB), LAI, aboveground biomass (AB), root biomass (RB) | $P_{BIAS}$ (%) | NSE | $R^2$ |
|---|---|---|---|---|---|---|
| Hybrid poplar | 1111 | High | AWB (t/ha) | 2 | 0.81 | 0.98 |
| | 83 | High | LAI | 4 | 0.96 | 0.76 |
| | | | AWB (t/ha) | −9 | 0.95 | 0.79 |
| | 25 | Medium | LAI | −11 | 0.98 | 0.98 |
| | | | AWB (t/ha) | −22 | 0.96 | 0.96 |
| | 8 | Low | AWB (t/ha) | 1 | 0.99 | 0.99 |
| Cottonwood | 23 | Medium | AB (t/ha) | −0.3 | 0.99 | 0.99 |
| | | | RB (t/ha) | 2 | 0.99 | 0.99 |

bias ($P_{\mathrm{BIAS}}$, %), Nash-Sutcliff model efficiency (NSE), and coefficient of determination ($R^2$) methods. Evaluation results of modeled outputs are shown in Table 8. Projected MABI values by the modified ALMANAC were compared with measured yields and projected values from the original ALMANAC and FOREST and modified FOREST models for hybrid poplar growth in Rhinelander, WI (Table 9).

Projected annual LAI of hybrid poplar with populations of 83 and 25 trees/100 $m^2$ had a good match with observed values (Fig. 7). Moreover, NSE ($R^2$) values for modeled LAI of hybrid poplar with populations of 83 and 25 trees/100 $m^2$ were 0.96 (0.76) and 0.98 (0.98), respectively (Table 8). Overall performance of the modeled LAI of hybrid poplar (83 and 25 trees/100 $m^2$) was satisfactory (since NSE ≥0.75 and $R^2$≥ 0.5). The optimal value of $P_{\mathrm{BIAS}}$ is 0, and 4 % (83 trees/ 100 $m^2$) was close to 0, which also represented accurate model simulation. However, $P_{\mathrm{BIAS}}$=−11 % (25 trees/100 $m^2$) meant that simulated annual LAI results were slightly overestimated, which also can be found from Fig. 7b. Simulated annual LAI values for years 3 and 4 were higher than observed values.

Overall performance of the modeled aboveground woody biomass yields of hybrid poplar (1111, 83, 25, and 8 trees/ 100 $m^2$) was satisfactory (since NSE ≥0.75 and $R^2$≥0.5). Projected annual aboveground woody biomass of hybrid poplar with populations of 1111, 83, 25, and 8 trees/100 $m^2$ fit observed values well (Fig. 8). Moreover, NSE ($R^2$) values for simulated aboveground woody biomass of hybrid poplar with populations of 1111, 83, 25, and 8 trees/100 $m^2$ were 0.81 (0.98), 0.95 (0.79), 0.96 (0.96), and 0.99 (0.99), respectively (Table 8). $P_{\mathrm{BIAS}}$ values of aboveground woody biomass of hybrid poplar with populations of 1111 and 8 trees/100 $m^2$ were 2 and 1 %, which also represented accurate model simulation. However, $P_{\mathrm{BIAS}}$ values of hybrid poplar with populations of 83 and 25 trees/100 $m^2$ were −9 and −22 % respectively, indicating that modeled annual aboveground woody biomass results were slightly overestimated, which also can be found from Fig. 8b (83 trees/100 $m^2$) and Fig. 8c (25 trees/ 100 $m^2$). Modeled annual aboveground woody biomass for years 2 and 3 was higher than observed values.

Projected annual aboveground biomass and root biomass of cottonwood with a population of 23 trees/100 $m^2$ fit the observed values well (Fig. 9). Moreover, NSE ($R^2$) values for modeled aboveground biomass and root biomass of cottonwood were 0.99 (0.99) and 0.99 (0.99), respectively (Table 8). Overall performance of the modeled aboveground and root biomass yields of cottonwood was satisfactory (since NSE ≥0.75 and $R^2$≥0.5). $P_{\mathrm{BIAS}}$ values of modeled aboveground and root biomass were −0.3 and 2 %, respectively, which also represented accurate model simulation.

Performance of MABI simulation by the modified ALMANAC was superior to the original ALMANAC and FOREST and the modified FOREST models. Measured MABI of the 5-year-old hybrid poplar planting with a population of 69 trees/

**Table 9** Comparison of projected and measured MABI of 5-, 9- and 10-year-old short-rotation intensively cultured hybrid poplar grown with various spacings in Wisconsin

| Variables | Age (year) | Spacing (m×m) | Population (trees/100 $m^2$) | Measured harvest | Modeled yields (t/ha/year) | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Modified ALMANAC | ALMANAC | FOREST | Modified FOREST |
| MABI (t/ha/year) | 5 | 1.2×1.2 | 69 | 7.6$^{a}$ | 7.0$^{b}$ (−8 %) | 10.0$^{b}$ (32 %) | 10.8$^{c,d}$ (42 %) | – |
| MABI (t/ha/year) | 10 | 2.4×2.4 | 17 | 10.4$^{e}$ | 9.2$^{b}$ (−12 %) | 1.9$^{b}$ (−82 %) | 20.4$^{c,d}$ (96 %) | 18.8$^{f}$ (81 %) |
| MABI (t/ha/year) | 9 | 3.6×3.6 | 8 | 6.2$^{e}$ | 7.3$^{b}$ (18 %) | 2.2$^{b}$ (−65 %) | 17.5$^{c,d}$ (182 %) | – |

Number in parentheses represents rate of increase/decrease of simulated results to related measured results

[a] Isebrands et al. [59]

[b] Present study

[c] Ek and Dawson [40]

[d] Ek and Dawson [58]

[e] Hansen [21]

[f] Meldahl [26]

100 $m^2$ was 7.6 t/ha/year (Table 9). The modified ALMANAC, original ALMANAC, and FOREST [40, 58] projections were 8 % (7.0 t/ha/year) lower, 32 % (10.0 t/ha/year) higher, and 42 % (10.8 t/ha/year) higher than the measured value, respectively.

Additionally, measured MABI of the 10-year-old hybrid poplar planting with a population of 17 trees/100 $m^2$ was 10.4 t/ha/year (Table 9). The modified ALMANAC, original ALMANAC, and FOREST [40, 58] and the modified FOREST [26] projections were 12 % (9.2 t/ha/year) lower, 82 % (1.9 t/ha/year) lower, 96 % (20.4 t/ha/year) higher, and 81 % (18.8 t/ha/year) higher than the measured value, respectively.

Measured MABI of the 9-year-old hybrid poplar planting with a population of 8 trees/100 $m^2$ was 6.2 t/ha/year (Table 9). The modified ALMANAC, original ALMANAC, and FOREST [40, 58] projections were 18 % (7.3 t/ha/year) higher, 65 % (2.2 t/ha/year) lower, and 182 % (17.5 t/ha/year) higher than the measured value, respectively.

## Conclusions

SRWCs such as hybrid poplar and cottonwood are important biofuel feedstocks. To simulate biomass yields of hybrid poplar and cottonwood appropriately, the functional components and parameters of hybrid poplar and cottonwood were determined, and related algorithms improved in ALMANAC for leaf area, plant biomass, and biomass partitioning. The improved tree growth simulation in ALMANAC was applied to hybrid poplar plots in Wisconsin and cottonwood plots in Mississippi. The simulated LAI, total biomass, and biomass partitioning between above-ground and roots were compared with published data to modify and evaluate the location-specific ALMANAC model parameters.

Simulated aboveground woody biomass and LAI results from the modified ALMANAC for the hybrid poplar site with various spacings in Wisconsin were satisfactory ($P_{\mathrm{BIAS}}$ −22~4, NSE 0.81~0.99, and $R^2$ 0.76~0.99). Additionally, modeled aboveground biomass and root biomass for the cottonwood site in Mississippi were good ($P_{\mathrm{BIAS}}$ −0.3~2, NSE 0.99~0.99, and $R^2$ 0.99~0.99). Generally, simulations by the modified ALMANAC model of LAI and biomass yield of *Populus* were good ($P_{\mathrm{BIAS}}$ −22~4, NSE 0.81~0.99, and $R^2$ 0.76~0.99) and improved relative to simulations by the original ALMANAC, FOREST, and modified FOREST models. Thus, the new algorithm for estimating LAI development for *Populus* (Eq. (1)), the new equation for calculating falling leaves weight (Eq. (3)), and suggested values of newly added parameter tree leaf factor (Table 5 and Eq. (2)) for various populations (high, medium, and low density) were reasonable. The suggested values and potential parameter range for hybrid poplar and cottonwood (Table 7) were reasonable, which provide guidance for simulation of poplar growth in the midwestern USA and cottonwood growth in the southern USA. The modified ALMANAC model is able to simulate biofeedstock production of juvenile and mature *Populus* trees with various populations. The improved algorithms of LAI and biomass simulation for tree growth could also be used in other process-based models, such as Soil and Water Assessment Tool (SWAT), Environmental Policy Integrated Climate (EPIC), and Agricultural Policy/Environmental eXtender (APEX).

The LAI and biomass yield data of *Populus* trees used in this work were from previous studies during 1970–1980 or 1995–1997. The data were limited (for some tree populations, only 4-year data were observed). Moreover, tree planting techniques and applied pesticide were different from those in recent hybrid poplar trials. Short-rotation woody crop growth models and parameters could potentially be improved using additional *Populus* tree growth data. Moreover, suggested ranges and values for *Populus* growth parameters could be adjusted in specific regions before being used for tree growth simulation.

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