Article

Simulating Biomass Production and Water Use of Poplars in a Plantation Using a STELLA-Based Model

Ying Ouyang [1,*] **, Satyanarayan Dev** [2] **, Johnny M. Grace III** [3] **, Devendra M. Amatya** [4] **and Theodor D. Leininger** [5]

[1] USDA Forest Service, Center for Bottomland Hardwoods Research, 775 Stone Blvd., Thompson Hall, Room 309, Mississippi State, MS 39762, USA

[2] Biological Systems Engineering, Florida A&M University, 1409, Wahnish Way, Tallahassee, FL 32303, USA; satyanarayan.dev@famu.edu

[3] USDA Forest Service, Center for Forest Watershed Research, 1740 S. Martin Luther King Jr. Blvd., Perry-Paige Bldg., Suite 303 North, Tallahassee, FL 32307, USA; johnny.m.grace@usda.gov

[4] USDA Forest Service, Center for Forest Watershed Research, 3734 Highway 402, Cordesville, SC 29434, USA; devendra.m.amatya@usda.gov

[5] USDA Forest Service, Center for Bottomland Hardwoods Research, 432 Stoneville Road, Stoneville, MS 38776, USA; theodor.leininger@usda.gov

* Correspondence: ying.ouyang@usda.gov

Abstract: Poplar trees (*Populus spp.*) are some of the fastest growing hardwoods used for biomass production. There are, however, conflicting observations about water use of poplars associated with the impact on local water resources. A STELLA (Structural Thinking and Experiential Learning Laboratory with Animation) model was modified to investigate the aboveground biomass production and water use in a mature (6 to 8 yrs. old) poplar plantation for a 3-year simulation period. The model predicted the typical annual pattern of soil evaporation, root water uptake, and leaf water transpiration in the poplar plantation increasing from winter to summer followed by respective decreases from summer to winter. Root water uptake and leaf water transpiration were proportional to the soil water content. More water was needed to produce the same amount of biomass during summer than during other seasons. Less water was consumed to produce the same amount of biomass as the age of the poplar trees increased. The net increase in biomass over the 3-year period was 0.69×10^4 kg/ha, which was equivalent to a 65% increase in biomass. The average rate of daily water use to daily biomass production was 1.05×10^9 cm³ water/kg biomass/ha. A good linear correlation between cumulative biomass production (CBP) and cumulative water use (CWU) was identified: $Y_{CBP} = 0.001 * X_{CWU}$, $R^2 = 0.99$, $p < 0.001$. This simple correlation provides a very good reference to estimate poplar water use efficiency (i.e., ratio of water use to biomass production) in growing regions where water resources are a limiting factor.

Keywords: biomass production; poplar; STELLA model; water use

1. Introduction

Poplar trees (*Populus spp.*) are fast-growing and high-yielding hardwoods that are some of the most important woody plants used by man. Trees in this genus have been used for constructing homes, making tools and medicines, and protecting riverbanks for thousands of years throughout the world [1]. Poplars have been planted commercially for the pulp and paper industry prior to 1965 [2], and in recent decades, they were used for phytoremediation, soil carbon sequestration, sediment run-off reduction, water quality protection, greenhouse gas emission mitigation, and wildlife habitat improvement [3–6]. Short rotation poplars (a cycle of 3–6 years) have been included in the U.S. Department of Energy's Bioenergy Feedstock Development Program since the late 1970s. The primary goal of this program is to produce fuel for cogeneration of heat and electricity [7]. Poplars

have a high biomass production rate (10–15×10^4 kg/ha/yr) and offer an environmentally sustainable way of generating heat and electricity [8–10].

There are, however, conflicting observations about water consumption by poplars and its impact on local water resources [10,11]. Normally, and especially in warm climates, poplars would consume large amounts of water to produce large volumes of biomass [12,13]. This could result in a negative effect on local water resources [14]. Bungart and Hüttl [15] reported mean annual transpiration rates of 266 and 241 mm, respectively, for two different poplar clones (*Beaupré, Populus trichocarpa x P. deltoides* and *Androscoggin, P. maximowiczii*) from 1996 to 2002 in the Lusatian mining region in Germany. Several studies have concluded that water use of poplars is substantially higher than that of conventional agricultural crops or grasslands [16]. In contrast, other studies argued that water use of poplars is comparable to that of crops and grasses [17,18].

The biomass yield of poplars depends on conditions of age, climate, clone, density, and silviculture [1]. In general, poplar yield varies with location. It has been estimated that yields range from 1.25 to 3.35×10^4 dry kg/acre/yr in the Lake states with a growth cycle of 5–8 years [19], 2.45 to 5.13×10^4 dry kg/acre/yr in the Upper Midwest with a growth cycle of 13 years [20], 2.01–2.99×10^4 dry kg/acre/yr in the Mississippi River Valley with a growth cycle of 8–10 years [21], and 3.08–8.61×10^4 dry kg/acre/yr in Minnesota with a growth cycle of 6–11 years [2]. Davis [22] reported that the best way to increase the biomass of poplars is to select the best clones for site-specific conditions.

A couple of simulation models have been developed to predict short rotation poplar growth and yield. Sampson and Ceulemans [23] developed the process-based SECRETS (Stand to Ecosystem CaRbon and EvapoTranspiration Simulator) model to simulate the growth and yield of mixed forests with different species. The model incorporates several modules, including light penetration, photosynthesis, surface and soil litter, carbon and nitrogen pools, carbon storage and partitioning, and biomass. Deckmyn et al. [24] modified and applied the SECRETS model to simulate poplar growth and yield in short rotation coppice plantations in Flanders, Belgium. These authors suggested that the process-based model was useful in predicting the effects of management strategies on poplar growth and yield. Hart et al. [25] applied the 3PG (Physiological Principles in Predicting Growth) model to simulate poplar growth in the Pacific Northwest. Their results showed that an updated 3PG model can be applied for coppiced short rotation woody crop plantings and biomass yield estimates under different irrigation patterns and weather conditions.

Although the aforementioned experimental and modeling studies have provided valuable insights into our understanding of poplar growth and yield, many of the hydrological processes and poplar water use dynamics are not included in these studies. Recently, Ouyang et al. [26] developed a STELLA (Structural Thinking and Experiential Learning Laboratory with Animation) model to estimate water use, among other variables, in a poplar plantation. The goal of this study was to predict the biomass production and water use of poplars in short rotation plantations by modifying the previously developed STELLA model. STELLA is a computer software program used to develop models for research with applications in economics, sciences, and engineering. Detailed descriptions of the STELLA software can be found elsewhere [27,28] (https://www.iseesystems.com/store/products/, accessed on 25 December 2021). Our specific objectives were to (1) incorporate biomass production calculations into the previous STELLA model for simulating biomass production and water use simultaneously; (2) calibrate the modified STELLA model with field data; and (3) apply the model to estimate biomass production and water use.

2. Materials and Methods

2.1. STELLA Model Description

A schematic diagram showing the water dynamics in a poplar plantation is shown in Figure 1. This diagram has been used to develop a STELLA model for simulating poplar water use and nitrogen (N) uptake [26]. The hydrological process module of the previous STELLA model consists of surface runoff, rainfall/irrigation, infiltration,

evaporation, percolation, and water uptake by roots as part of tree transpiration. The model was calibrated and validated for soil water drainage and nitrate concentration with good agreement [26] between model predictions and measured values reported by Lee and Jose [29]. A simulation scenario was performed to estimate the diurnal and monthly water and N dynamics of a poplar plantation. Although an elaborate description of the model is beyond the scope of this study and can be found in Ouyang et al. [26], a brief outline of the mathematical functions for the major soil physical and hydrological processes is given below for the readers' convenience.
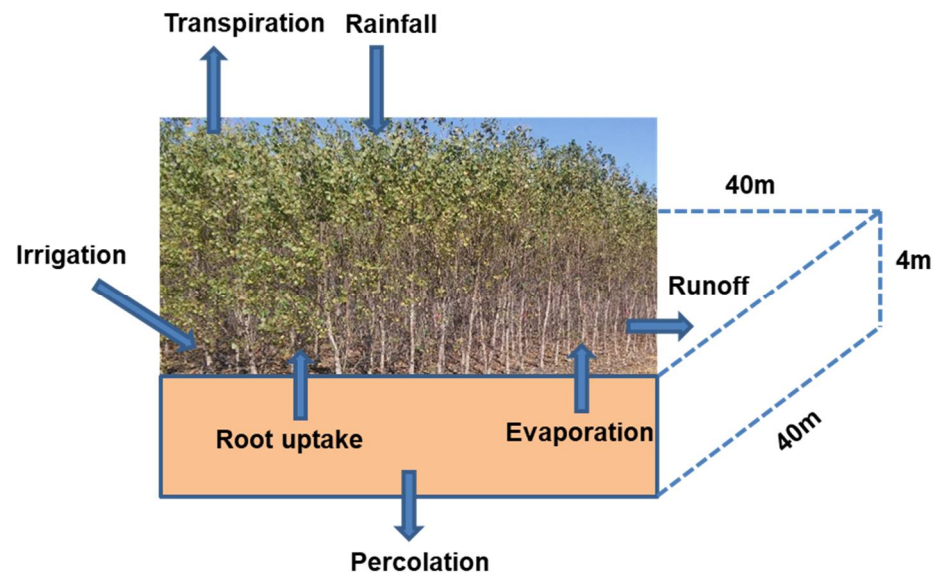

Figure 1. Schematic diagram showing the soil hydrological processes in a poplar plantation.

Soil surface water runoff is estimated as [30,31]:

$$R_o = \frac{(R - 0.2S)^2}{(R + 0.8S)} \tag{1}$$

where R_o is the surface runoff (cm^3/h), R is the rainfall rate (cm^3/h) and S, the watershed retention parameter, is estimated by

$$S = \frac{1000}{CN} - 10 \tag{2}$$

where CN is the runoff curve number. Curve number is a function of soil type, soil physical properties, crop type, and management practices and is equal to 81 for the study site comparable to this research [30].

The canopy interception is calculated as [32]

$$S_t = S_c[1 - \exp\left(-\frac{RI}{S_c} - \frac{RA}{S_c}\right)] \tag{3}$$

where S_t is the storage of rainfall amount (cm^3), S_c is the storage capacity (cm^3), RI is the present rainfall amount (cm^3), and RA is the previous rainfall amount (cm^3). Equation (3) is valid if tree canopy is dry before rainfall events.

The net rainfall rate is calculated by subtracting actual rainfall with canopy interception:

$$\text{NR} = (R - S_t)/time \tag{4}$$

Soil evaporation is estimated by fitting a Gaussian-type function to measured data from a poplar plantation [29]:

$$S_{evp} = \left(a_1 EXP\left[-0.5\left(\frac{TY-a_2}{a_3}\right)^2\right]\right) \quad (R^2 = 0.961, \; p \; < \; 0.001) \tag{5}$$

where S_{evp} is the soil evaporation (cm^3/h), TY is the time of year (h), and a_1 to a_3 are the coefficients (Table 1).

Leaf water transpiration is approximated in a similar way as that of Equation (5):

$$L_{trp} = a_4\left[-0.5\left(\frac{TY-a_2}{a_3}\right)^2\right] \quad (R^2 = 0.981, \; p \; < \; 0.001) \tag{6}$$

where L_{trp} is the leaf water transpiration (cm^3/h), and a_4 is the coefficient (Table 1). For transpiration of a mature plantation, a forest cover factor of 0.85 is also included in the STELLA model. For different study sites, the constants in Equations (5) and (6) are suggested to change based on measured data.

Soil water percolation is calculated as [31]

$$Q = \alpha \; (\theta - f_c) \tag{7}$$

where Q is the percolation rate (cm^3/h), α is the drainage coefficient (cm^3/h), θ is the volumetric water content (cm^3/cm^3), and f_c is the field water capacity (cm^3/cm^3).

The root water uptake is given as [26,33]

$$Q_{root} = \frac{L_{trp}}{0.99} \tag{8}$$

where Q_{root} is the soil water uptake rate (cm^3/h).

Rainfall data were obtained from local weather stations, whereas irrigation rates were from Lee and Jose [29]. The reasons to select the study site used by Lee and Jose [29] for our model applications are that this site has sufficient input data for hydrologic, soil, poplar growth, and climate conditions. It should be noted that there are some assumptions for using Equations (1) and (5)–(8). These included: (1) soil evaporation was assumed to cease when the soil water content was below 0.15 cm^3/cm^3 because of insufficient soil water supply or when it was raining because of saturation vapor pressure; (2) leaf transpiration was assumed to cease when it was raining because of saturation vapor pressure and stomata close or near zero at night; (3) plantation irrigation started from spring to fall when soil water content is below 0.15 cm^3/cm^3 (wilting point); and (4) soil percolation occurred only when soil water content was greater than field capacity. All of them have been incorporated into the modified STELLA model.

In this study, a new module, i.e., the biomass production module, was added to the STELLA model as detailed below. The total aboveground biomass of a poplar tree is calculated as [34]

$$B_m = Exp(\beta_0 + \beta_1 Ln(dbh)) \tag{9}$$

where B_m is the total aboveground biomass (kg) for a tree with a *dbh* of 2.5 cm or larger, *dbh* is the diameter at breast height (cm), and β_0 and β_1 are the coefficients characterizing biomass production of poplars (Table 1).

Table 1. Major input parameter values used in this study.

Parameter	Value or Empirical Equation	Source
Curve number (CN) in Equation (2)	81	USDA [30]
Storage capacity (S_c) in Equation (3)	3.5	Calibrated

Table 1. *Cont.*

Parameter	Value or Empirical Equation	Source
a_1 in Equation (5)	0.034	Calculated based on data from Lee and Jose [29]
a_2 in Equation (5)	4345	Calculated based on data from Lee and Jose [29]
a_3 in Equation (5)	2800	Calculated based on data from Lee and Jose [29]
a_4 in Equation (6)	0.627	Calculated based on data from Lee and Jose [29]
a_5 in Equation (10)	3.473	Edmondson et al. [35]
a_6 in Equation (10)	8760	Edmondson et al. [35]
a_7 in Equation (10)	0.59	Edmondson et al. [35]
Rainfall (cm/h)	Time series measurements	Local weather station
Irrigation (cm/h)	0.3	Lee and Jose [29]
Soil area (cm^2)	1,000,000,000 (or one hectare)	Lee and Jose [29]
Soil depth (cm)	200	Lee and Jose [29]
Soil porosity (cm^3/cm^3)	0.35	Ouyang et al. [26]
Field capacity	0.3	Ouyang et al. [26]
Drainage coefficient (cm/h)	0.005	Calibrated
Initial soil water (cm^3)	33,600,000,000	Calculated based on soil volume and water content
Initial root water (cm^3)	2,450,000,000	Estimated from Jenkins et al. [35] and Lee and Jose [29]
Initial stem water (cm^3)	816,666,667	Estimated from Stem volume index [29]
Initial leaf water (cm^3)	816,666,667	Estimated from Jenkins et al. [35] and Lee and Jose [29]
Transpiration (cm^3/h/tree)	0.016	Lee and Jose [29]
Plant density (tree/ha)	229	Lee and Jose [29]
Forest cover factor	0.85	Assumed based on our observations
$\beta 0$ in Equation (9)	-1	Jenkins et al. [34]
$\beta 1$ in Equation (9)	2.1	Jenkins et al. [34]

Dbh is assumed to be a function of poplar age [35] and is given as

$$dbh = a_5 \left(\frac{Age}{a_6} \right)^{a_7} \tag{10}$$

where *Age* is the age of the poplar (h) and a_5 to a_7 are coefficients (Table 1).

The ratio of water use to biomass production for a single tree is then calculated as

$$W = \frac{T_w}{B_m} \tag{11}$$

where *W* is the ratio (cm^3/kg), and *Tw* is the volume of transpiration water by the poplar (cm^3). To calculate the ratio in a poplar plantation, Equations (9) and (11) are multiplied by the tree density of the plantation.

Equations (9)–(11) were incorporated into the exiting STELLA model. Figures 2 and 3 are maps of the modified STELLA model for simultaneously simulating hydrological processes and biomass production.
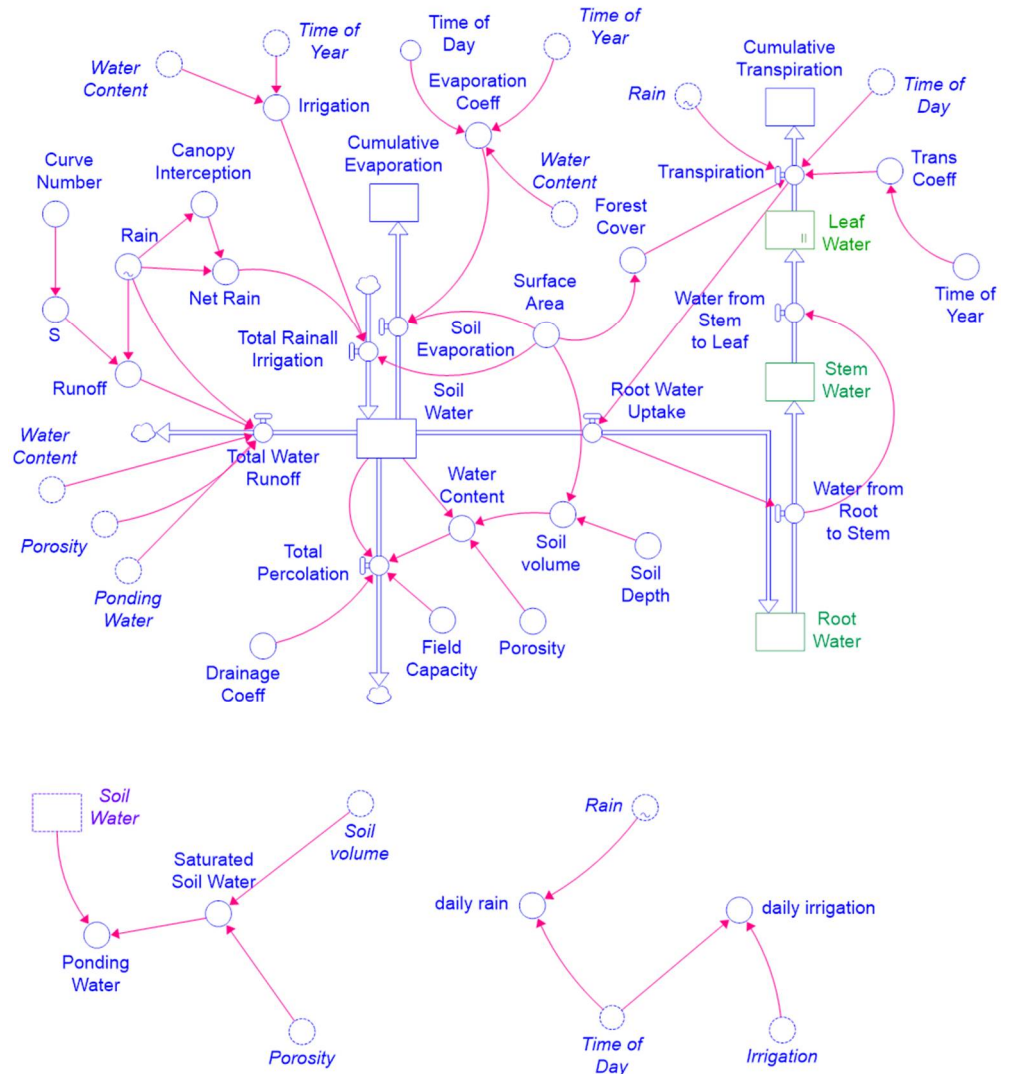
Hydrological Processes in a Plantation

Figure 2 content.

Figure 2. A map of the STELLA model for simulating hydrological processes.

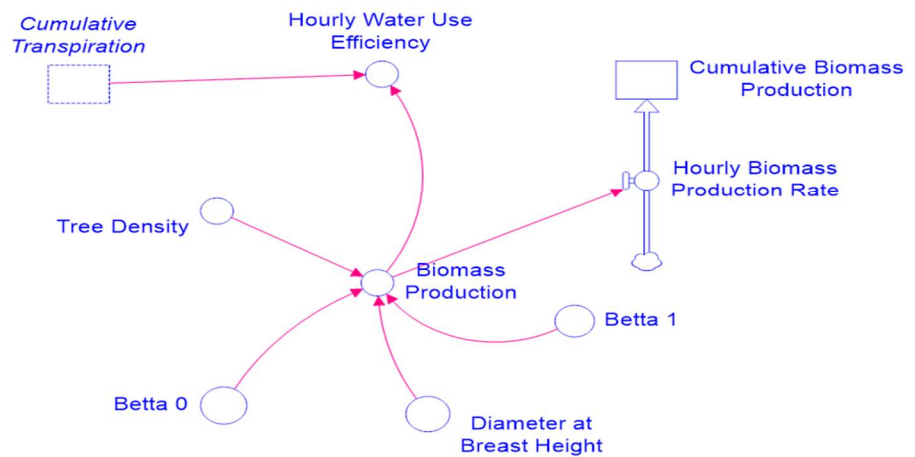## Biomass Production in a Poplar Plantation

Figure 3 content.

Figure 3. A map of the STELLA model for simulating biomass production.

2.2. Data Acquisition

The majority of model input data used in this study were obtained from Lee and Jose [29] and Henderson and Jose [36]. These authors investigated soil water drainage and biomass production of three short rotation woody crop species under varying nitrogen and water availability in Santa Rosa County, FL, USA. More specifically, the input data for hydrological processes and poplar biomass production were obtained from their reports, whereas the rainfall data were obtained from the local weather station in Santa Rosa County for a period from 1 January 2001 to 31 December 2003. The input data such as soil physical property and coefficients in equations were from other studies that were cited in Table 1.

2.3. Model Calibration

Since the previous STELLA model [26] was modified to add the canopy rainfall interception and biomass production, the modified STELLA model was re-calibrated in this study. The hydrological process module was calibrated using the experimental data reported by Lee and Jose [29], whereas the biomass production module was calibrated using the experimental data reported by Henderson and Jose [36]. For the biomass production calibration, we selected the data for biomass production of poplars under two treatments (i.e., control without fertilization and applying 56 kg N/yr/ha) reported by Henderson and Jose [36]. These authors measured the annual biomass production at ages of 6, 7, and 8 (three data points) for each treatment. Two simulations were performed with one for control treatment and the other for applying 56 kg N/yr/ha treatment. Table 1 listed the major input data used during the model calibration.

Comparisons of the observed and predicted soil water drainage and biomass production of the poplars are shown in Figure 4. The regression equation for soil water drainage was $Y_{Prediction} = 0.67X_{Measurement}$ with $R^2 = 0.76$, nRMSE (normalized root mean square error) = 0.27, NSE (Nash Sutcliff efficiency) = 0.35, and $p < 0.01$, while the regression equation for biomass production was $Y_{Prediction} = 1.002X_{Measurement}$ with $R^2 = 0.99$, nRMSE = 0.063, NSE = 0.88, and $p < 0.001$. With these good statistical measures, we concluded that the modified STELLA model predicted the soil hydrological processes and biomass production of the poplars reasonably well.

A simulation scenario was developed to assess the biomass production of the mature poplar trees (*P. deltoides*) and their water use for a 3-year period with the poplars starting at age 6. The modeled domain used in this study has an area of one hectare with a soil depth of 4 m (Figure 1). All the simulation conditions and input parameter values were the same as those used for the model calibration except for no fertilizer application, and the plantation was irrigated only when the soil water content was equal to or below the wilting point (0.15 cm^3/cm^3). This simulation scenario reflects the field study site conditions in Santa Rosa County, FL, USA, used by Lee and Jose [29]. The simulation started on 1 January and ended on 31 December of the third year with an hourly simulation time step.
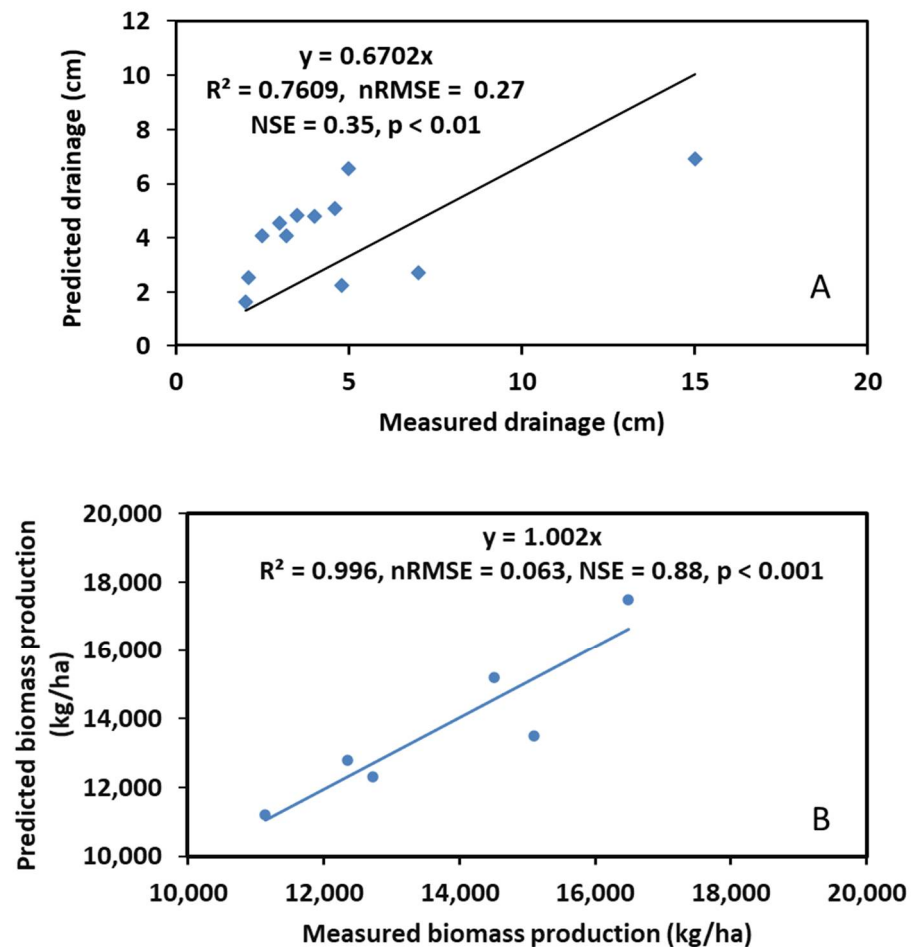
Figure 4. Comparison of model predicted and field measured soil water drainage (**A**) and biomass production (**B**) during model calibration.

3. Results and Discussion

3.1. Soil Hydrological Processes

Annual variations in measured daily rainfall along with simulated irrigation, soil water content, and soil evaporation in the plantation for a 3-year simulation period are shown in Figure 5. As stated above, the plantation irrigation was turned on from spring to fall when the soil water content was equal to or less than 0.15 cm^3/cm^3. In other words, no irrigation occurred during winter as water use by poplars was trivial during this season. The frequencies of plantation irrigation were negatively related to rainfall events (Figure 5A,B). The number of irrigations were 2 and 3, respectively, in the first- and second-year's simulations. As expected, more irrigations occurred in the second year because of fewer rainfall events and lower soil water content (Figure 5C). Simulation results confirmed that irrigations were sometimes required for poplars under normal growing conditions.

Comparison of Figure 5A,C revealed that soil water content corresponded to rainfall events. That is, an increase in rainfall rate increased soil water content. For example, the soil water content was 0.31 cm^3/cm^3 at Day 850 in Year 3 when the rainfall rate was 10 cm^3/d but was 0.21 cm^3/cm^3 at Day 951 when the rainfall rate was 5 cm^3/d. A 2-fold increase in rainfall rate increased the soil water content by 1.5 times. These results suggest that the STELLA model appropriately predicted soil hydrological processes.

A typical annual soil evaporation pattern, with an increase from winter to summer followed by a decrease from summer to winter, is shown in Figure 5D. The highest rate of soil evaporation was about 3.63×10^7 $cm^3/d/ha$ during summer and occurred because of warmer summer temperatures, which was calculated by Equation (5). The abrupt changes

in soil evaporation (Figure 5D) occurred when the soil water content was equal to or less than 0.15 cm^3/cm^3 because of insufficient soil water supply for evaporation.
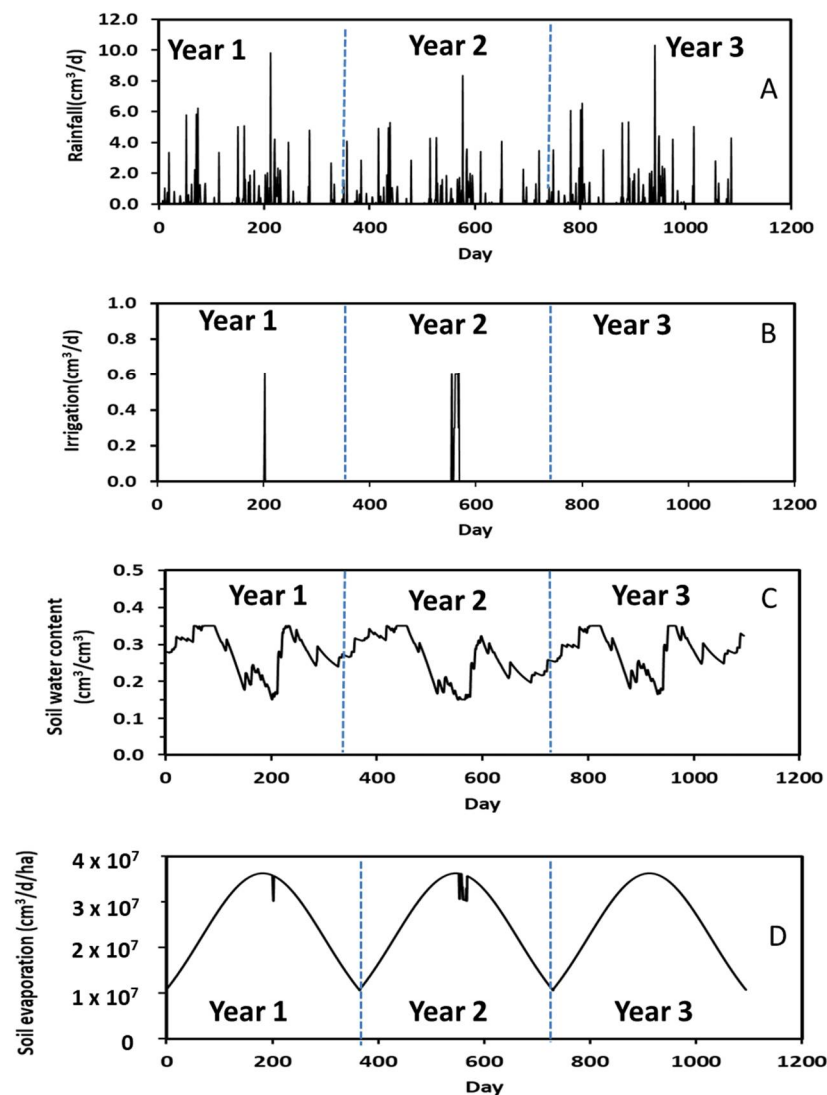

Figure 5. Measured daily rainfall along with simulated irrigation, water content, and soil evaporation during the 3-year period.

3.2. Poplar Water Dynamics

Annual changes in daily poplar leaf water transpiration, root water uptake, and soil water storage are given in Figure 6. Analogous to soil evaporation, a characteristic annual pattern was observed in leaf transpiration and root uptake, i.e., increasing from winter to summer followed by decreasing from summer to winter. The highest rate of leaf water transpiration was 5.69×10^8 cm^3/d/ha during summer driven by warmer temperatures. More water is needed for leaf transpiration in summer than in fall and winter.

Leaf transpiration was affected by rainfall events and decreased with increasing rainfall rate and duration. For instance, there were more rainfall events between Days 224 to 235 in Year 1 (Figure 5A), which resulted in decreases in leaf water transpiration during this period (Figure 6A). In this study, we assumed that little to no leaf transpiration occurs during rainfall. The water vapor density is normally saturated if it is raining, and leaf transpiration ceases on a wet day [33]. Leaf transpiration was also affected by soil water storage. Analogous to rainfall events, low soil water storage reduced the leaf transpiration rates. The rate was 2.66×10^8 cm^3/d/ha on Day 911 in Year 3 (Figure 6A) when the soil water storage was 1.81×10^{10} cm^3 (Figure 6C), whereas the rate was 4.4×10^8 cm^3/d/ha in

Day 967 in Year 3 (Figure 6A) when the soil water storage was 3.42×10^{10} cm^3 (Figure 6C). A 1.9-fold decrease in soil water storage decreased leaf water transpiration by a factor of 1.7. This occurred because there was less water in the soil for leaf transpiration. A similar annual pattern was observed in root water uptake. In other words, root water uptake increased from winter to summer and then decreased from summer to winter. Comparison of Figure 6B,C revealed that root water uptake was correlated to soil water storage. More specifically, an increase in root water uptake decreased soil water storage. Additionally, the daily leaf water transpiration rate (Figure 6A) had a similar variation pattern but slightly lower as compared to the root water uptake rate (Figure 6B). This occurred because 99% of water taken up by roots was lost through leaf transpiration based on Equation (8).
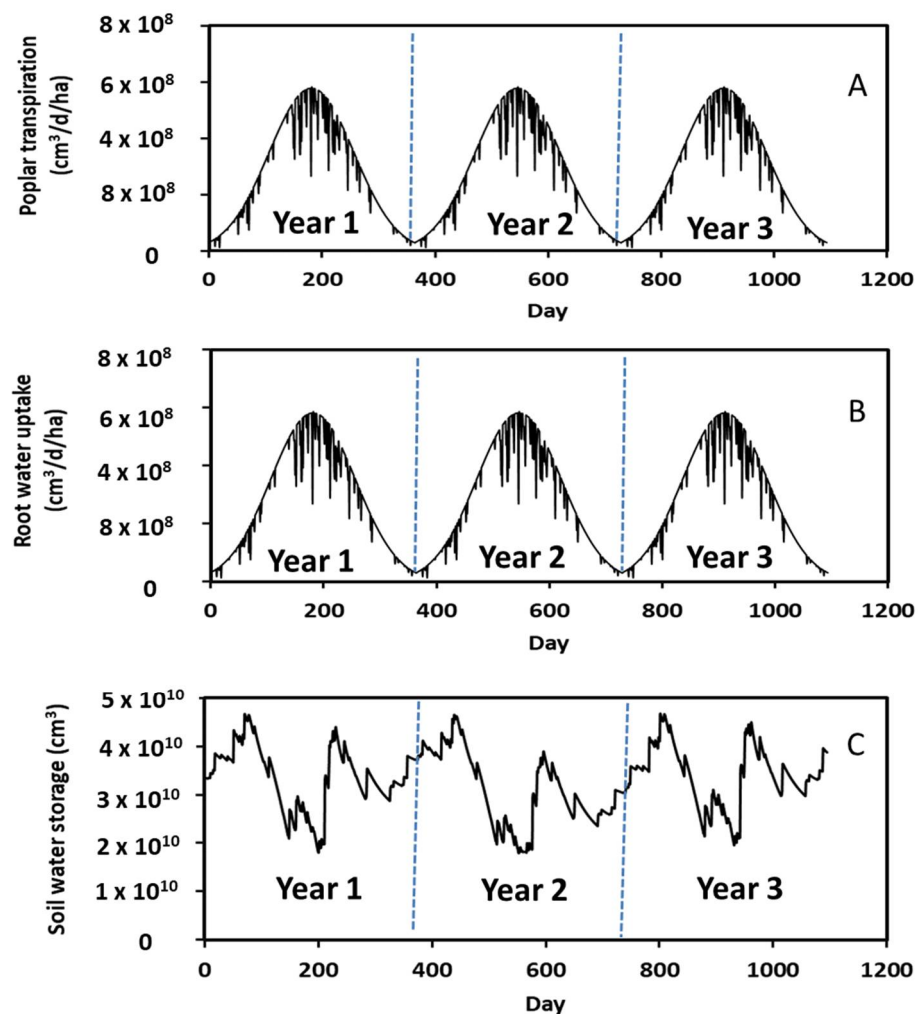

Figure 6. Simulated daily leaf transpiration, root water uptake, and soil water storage during the 3-year period.

3.3. Biomass Production and Water Use Efficiency

Simulated biomass production of poplars over a 3-year period (i.e., between ages 6 and 8) is shown in Figure 7A. This figure shows the annual growth pattern, increasing from winter to summer and then decreasing from summer to next winter. Overall, the biomass production increased with ages. The net increase in biomass over the three years was 0.69×10^4 kg/ha, a 65% increase. The 3-year average annual biomass production was 2.3×10^4 kg/ha. This finding was comparable to that reported by Henderson and Lee [36]. These authors stated that the average annual biomass production of poplars from ages 6 to 8 is 1.37×10^4 kg/ha.
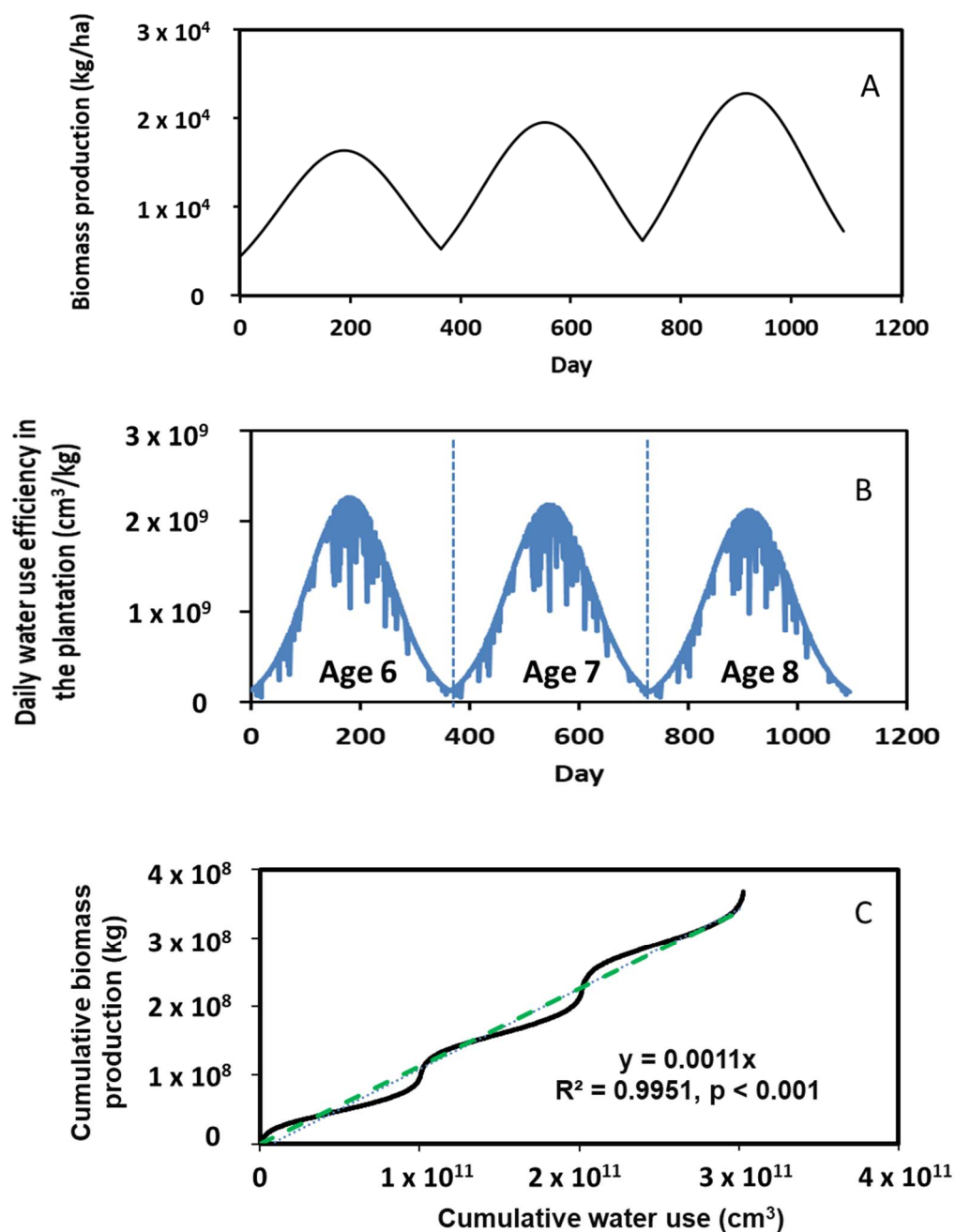
Figure 7. Simulated biomass production, water use efficiency, and relationship of cumulative biomass and water use during the 3-year period.

Daily water use efficiency (WUE) over the 3-year simulation period is given in Figure 7B, which was calculated by dividing daily leaf water transpiration with daily biomass production. A typical annual pattern in WUE was predicted with more water being consumed to produce poplar biomass during summer. The average daily WUE was 1.05×10^9 cm^3/kg/ha over the 3-year simulation period. Our simulations further revealed that the maximum annual water use decreased as the poplars aged. For instance, the maximum daily water use was 2.23×10^9 cm^3/kg/ha at age 6, 2.19×10^9 cm^3/kg/ha at age 7 and 2.07×10^9 cm^3/kg/ha at age 8. It is apparent that less water was consumed to produce the same amount of biomass as time elapsed. This might be because there was an increasing WUE as the trees grow, but WUE plateaued upon maturity.

A linear correlation between cumulative biomass production and cumulative water use was identified (see the dashed line in Figure 7C) as

$$Y_{CBP} = 0.001 * X_{CWU} \ (R^2 = 0.995, p < 0.001) \tag{12}$$

where Y_{CBP} is the cumulative biomass production (kg), and X_{CWU} is the cumulative water use (cm^3). Our literature search showed that no simulation has been accomplished to establish such a correlation. This correlation created a good reference for estimating the production of bioenergy plants in response to their water use, which could be useful for biomass producers to assess WUE in regions where overuse of water resources is a concern.

4. Conclusions

A typical annual variation pattern was simulated for soil evaporation, root water uptake, and leaf water transpiration, all of which increased from winter to summer followed by a decrease from summer to winter.

Water use efficiency revealed that more water was consumed to produce the same amount of biomass during summer than other seasons, whereas less water was consumed to produce the same amount of biomass as time elapsed and tree age increased, although the reasons for this phenomenon remain to be investigated.

A very good linear correlation between cumulative biomass production and cumulative water use was identified in this study. Our literature search showed that few studies have been conducted to establish such a correlation. This correlation revealed a good reference for estimating production of bioenergy plants in response to their water use.

It should be noted that groundwater and vadose zone water interaction was not included although the STELLA model covered soil water percolation. We also want to caution readers that the STELLA model was not validated because insufficient measured data are available for this purpose. Although most of the model input data were obtained from the same study site, there were some input data from other locations. Further study is, therefore, warranted to add the interaction for those plantations with shallow groundwater aquifer and validate the model using all of the input data from the same study site.

Author Contributions: Conceptualization, Y.O.; methodology, Y.O.; software, Y.O.; validation, Y.O.; data curation, Y.O.; writing—original draft preparation, Y.O.; writing—review and editing, S.D., J.M.G.III, D.M.A. and T.D.L. All authors have read and agreed to the published version of the manuscript.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are reported in the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Farm Energy and Wood Energy, Poplar (*Populus spp.*) Trees for Biofuel Production. Farm Energy, Wood Energy 6 May 2014 (20140506). Available online: https://farm-energy.extension.org/poplar-populus-spp-trees-for-biofuel-production/ (accessed on 27 September 2021).
2. Berguson, W.E.; Eaton, J.; Stanton, B. Development of hybrid poplar for commercial production in the United States: The Pacific Northwest and Minnesota experience. In *Sustainable Alternative Fuel Feedstock Opportunities, Challenges and Roadmaps for Six U.S. Regions*; Braun, R., Karlen, D., Johnson, D., Eds.; Soil and Conservation Society: Ankeny, IA, USA, 2010.
3. Stanton, B.; Eaton, J.; Johnson, J.; Rice, D.; Schuette, B.; Moser, B. Hybrid poplar in the Pacific Northwest: The effects of market-driven management. *J. Forestry* **2002**, *100*, 28–33.
4. González-García, S.; Gasol, C.M.; Gabarrell, X.; Rieradevall, J.; Moreira, M.T.; Feijoo, G. Environmental profile of ethanol from poplar biomass as transport fuel in Southern Europe. *Renew. Energy* **2010**, *35*, 1014–1023. [CrossRef]
5. Langeveld, H.; Quist-Wessel, F.; Dimitriou, I.; Aronsson, P.; Baum, C.; Schulz, U.; Bolte, A.; Baum, S.; Köhn, J.; Weih, M.; et al. Assessing Environmental Impacts of Short Rotation Coppice (SRC) Expansion: Model Definition and Preliminary Results. *BioEnergy Res.* **2012**, *5*, 621–635. [CrossRef]

6. Rizvi, R.H.; Singh, M.; Kumar, A.; Srivastava, S. Valuation of carbon sequestration by poplar based agroforestry systems in Yamunanagar, Haryana. *Indian J. Agric. Sci.* **2020**, *90*, 312–315.

7. Hansen, E.; Moore, L.; Netzer, D.; Ostry, M.; Phipps, H.; Zavitkovski, J. *Establishing Intensively Cultured Hybrid Poplar Planations for Fuel and Fiber*; USDA Forest Service General Technical Report NC-78; Department of Agriculture, Forest Service, North Central Forest Experiment Station: St. Paul, MN, USA, 1983.

8. Berndes, G.; Hoogwijk, M.; van den Broek, R. The contribution of biomass in the future global energy supply: A review of 17 studies. *Biomass Bioenergy* **2003**, *25*, 1–28. [CrossRef]

9. Aylott, M.J.; Casella, E.; Tubby, I.; Street, N.R.; Smith, P.; Taylor, G. Yield and spatial supply of bioenergy poplar and willow short-rotation coppice in the UK. *New Phytol.* **2008**, *178*, 358–370. [PubMed]

10. Bloemen, J.; Egi, R.; Ichot, S.F.; Horemans, J.A.; Broeckx, L.S.; Verlinden, M.S.; Zenone, T.; Ceulemans, R. Water use of a multigenotype poplar short-rotation coppice from tree to stand scale. *GCB Bioenergy* **2017**, *9*, 370–384. [CrossRef]

11. Ashworth, K.; Wild, O.; Hewitt, C.N. Impacts of biofuel cultivation on mortality and crop yields. *Nat. Clim. Chang.* **2013**, *5*, 492–496. [CrossRef]

12. Allen, S.J.; Hall, R.L.; Rosier, P.T.W. Transpiration by two poplar varieties grown as coppice for biomass production. *Tree Physiol.* **1999**, *19*, 493–501. [PubMed]

13. Navarro, A.; Facciotto, G.; Campi, P.; Mastrorilli, M. Physiological adaptations of five poplar genotypes grown under SRC in the semi-arid Mediterranean environment. *Trees* **2014**, *28*, 983–994. [CrossRef]

14. Fischer, M.; Trnka, M.; Kučera, J.; Deckmyn, G.; Orság, M.; Sedlák, P.; Žalud, Z.; Ceulemans, R. Evapotranspiration of a high-density poplar stand in comparison with a reference grass cover in the Czech–Moravian Highlands. *Agric. For. Meteorol.* **2013**, *181*, 43–60. [CrossRef]

15. Bungart, R.; Hüttl, R.F. Growth dynamics and biomass accumulation of 8-year-old hybrid poplar clones in a short-rotation plantation on a clayey sandy mining substrate with respect to plant nutrition and water budget. *Eur. J. For. Res.* **2004**, *123*, 105–115. [CrossRef]

16. Petzold, R.; Schwarzel, K.; Feger, K.H. Transpiration of a hybrid poplar plantation in Saxony (Germany) in response to climate and soil conditions. *Eur. J. For. Res.* **2011**, *130*, 695–706. [CrossRef]

17. Linderson, M.L.; Iritz, Z.; Lindroth, A. The effect of water availability on standlevel productivity, transpiration, water use efficiency and radiation use efficiency of field-grown willow clones. *Biomass Bioenergy* **2007**, *31*, 460–468. [CrossRef]

18. Tricker, P.J.; Pecchiari, M.; Bunn, S.M.; Vaccari, F.P.; Peressotti, A.; Miglietta, F.; Taylor, G. Water use of a bioenergy plantation increases in a future high CO$_2$ world. *Biomass Bioenergy* **2009**, *33*, 200–208. [CrossRef]

19. Miller, R.O.; Bender, B.A. Proceedings from Sun Grant National Conference for Biomass Feedstock Production and Utilization, New Orleans, LA, USA. Available online: https://bioenergykdf.net/content/proceedings-2012-sun-grant-national-conference-science-biomass-feedstock-production-and (accessed on 25 December 2021).

20. Zamora, D.; Wyatt, G.; Apostol, K.; Tschirner, U. Biomass yield, energy values, and chemical composition of 21/25 hybrid poplar in short rotation woody crops production and native perennial grasses in Minnesota, USA. *Biomass Bioenergy* **2013**, *49*, 222–230. [CrossRef]

21. Zalesny, R.S., Jr.; Hall, R.B.; Zalesny, J.A.; McMahon, B.G.; Berguson, W.E.; Stanosz, G.R. Biomass and genotype environment interactions of Populus energy crops in the Midwestern United States. *BioEnergy Res.* **2009**, *2*, 106–122. [CrossRef]

22. Davis, J.M. Genetic improvement of poplar (*Populus spp.*) as a bioenergy crop. In *Genetic Improvement of Bioenergy Crops*; Vermerris, W., Ed.; Springer Science & Business Media: Berlin, Germany, 2008.

23. Sampson, D.A.; Ceulemans, R. SECRETS: Simulated carbon fluxes from a mixed coniferous/deciduous Belgian forest. In *Forest Ecosystem Modelling, Upscaling and Remote Sensing*; Ceulemans, R.J.M., Veroustraete, F., Gond, V., Van Rensbergen, J.B.H.F., Eds.; SPB Academic Publishing: The Hague, The Netherlands, 2000; pp. 95–108.

24. Deckmyna, G.; Laureysensa, I.; Garciab, J.; Muysb, B.; Ceulemansa, R. Poplar growth and yield in short rotation coppice: Model simulations using the process model SECRETS. *Biomass Bioenergy* **2004**, *26*, 221–227. [CrossRef]

25. Hart, Q.J.; Tittmann, P.W.; Bandaru, V.; Jenkins, B.M. Modeling poplar growth as a short rotation woody crop for biofuels in the Pacific Northwest. *Biomass Bioenergy* **2015**, *79*, 12–27. [CrossRef]

26. Ouyang, Y.; Zhang, J.E.; Leininger, T.D.; Frey, B. A STELLA model to estimate water and nitrogen dynamics in a short-rotation woody crop plantation. *J. Environ. Qual.* **2015**, *44*, 200–209. [CrossRef]

27. Ouyang, Y.; Feng, G.; Renninger, H.; Leininger, T.D.; Parajuli, P.; Grace, J.M. A STELLA-Based Model to Simultaneously Predict Hydrological Processes, N Uptake and Biomass Production in a Eucalyptus Plantation. *Forests* **2021**, *12*, 515. [CrossRef]

28. Ouyang, Y.; Zhang, J.E.; Lin, D.; Liu, D.G. A STELLA model for the estimation of atrazine runoff, leaching, adsorption, and degradation from an agricultural land. *J. Soils Sediments* **2010**, *10*, 263–271. [CrossRef]

29. Lee, K.H.; Jose, S. Nitrate leaching in cottonwood and loblolly pine biomass plantations along a nitrogen fertilization gradient. *Agric. Ecosyst. Environ.* **2005**, *105*, 615–623. [CrossRef]

30. USDA-SCS. *National Engineering Handbook*; USDA–SCS: Washington, DC, USA, 1973.

31. Mullins, J.A.; Carsel, R.F.; Scarbrough, J.E.; Ivery, A.M. *PRZM-2, a Model for Predicting Pesticides Fate in the Crop Root and Unsaturated Soil Zones: User Manual for Release 2.0*; US-EPA; U.S. Department of Energy Office of Scientific and Technical Information: Athens, GA, USA, 1993.

32. Baiamonte, G. Simplified Interception/Evaporation Model. *Hydrology* **2021**, *8*, 99. [CrossRef]

33. Nobel, P.S. *Biophysical Plant Physiology and Ecology*; Freeman and Company: San Francisco, CA, USA, 1983.
34. Jenkins, J.C.; Chojnacky, D.C.; Heath, L.S.; Birdsey, R.A. *Comprehensive Database of Diameter-Based Biomass Regressions for North American Tree Species*; General Technical Report NE-319; USDA, Forest Service: Newtown Square, PA, USA, 2003.
35. Edmondson, J.; Friedman, J.; Meko, D.; Touchan, R.; Scott, J.; Edmondson, A. Dendroclimatic potential of plains cottonwood (*Populus deltoides* subsp. *monilifera*) from the northern great plains, USA. *Tree Ring Res.* **2014**, *70*, 21–30. [CrossRef]
36. Henderson, D.E.; Jose, S. Biomass production potential of three short rotation woody crop species under varying nitrogen and water availability. *Agrofor. Syst.* **2010**, *80*, 259–273. [CrossRef]