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A STELLA-Based Model to Simultaneously Predict Hydrological Processes, N Uptake and Biomass Production in a Eucalyptus Plantation

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Abstract: Eucalyptus is one of the fastest growing hardwoods for bioenergy production. Currently, few modeling tools exist to simultaneously estimate soil hydrological processes, nitrogen (N) uptake, and biomass production in a eucalyptus plantation. In this study, a STELLA (Structural Thinking and Experiential Learning Laboratory with Animation)-based model was developed to meet this need. After the model calibration and validation, a simulation scenario was developed to assess eucalyptus (*E. grandis* × *urophylla*) annual net primary production (ANPP), woody biomass production (WBP), water use efficiency (WUE), and N use efficiency (NUE) for a simulation period of 20 years. Simulation results showed that a typical annual variation pattern was predicted for water use, N uptake, and ANPP, increasing from spring to fall and decreasing from fall to the following winter. Overall, the average NUE during the growth stage was 700 kg/kg. To produce 1000 kg eucalyptus biomass, it required 114.84 m³ of water and 0.92 kg of N. This study suggests that the STELLA-based model is a useful tool to estimate ANPP, WBP, WUE, and NUE in a eucalyptus plantation.

Keywords: biomass; eucalyptus; N uptake; STELLA model; water use

1. Introduction

Eucalyptus (*Eucalyptus* spp.), native to Australia and Indonesia, is one of the fastest growing hardwoods and has been introduced into many parts of the world such as India, South Africa, South America, and South China [1–5]. These fast-growing trees can produce as much as 40 metric tons of dry matter per hectare per year in tropical regions [3,6]. Eucalyptus are identified as one of the best feedstocks for biofuels due to their fast growth rate and coppicing ability [7]. There are, however, concerns about their water consumption and potential adverse environmental impacts around the world [2,3,8–10]. Scott and Lesch [11] showed that eucalyptus cause 90 to 100% reduction in streamflow, while pines resulted in only 40–60% reduction in streamflow during the first eight years of growth. However, these differences may diminish as the pine stands become well-established. Studies from India [12] and South Africa [1] showed that when water resources are limited, the area, location, and management of eucalyptus plantations need to be carefully considered to

avoid conflict with other water users. Morris et al. [13] studied water use by eucalyptus plantations in South China. Their results suggest that annual water use by the eucalyptus plantations is about 550 mm and potential annual water use without soil water limitation is about 865 mm. Other studies showed that well-managed eucalyptus plantations are beneficial rather than detrimental to water use and the environment [14–16].

Depletion of soil nutrients, including nitrogen (N), by eucalyptus, has triggered concerns about the sustainability of forest plantations [17,18]. Guo et al. [18] investigated biomass production and nutrient cycling in eucalyptus forests in New Zealand and found that eucalyptus had the highest biomass and nutrient accumulation when either irrigated with wastewater (meat work effluent) or without irrigation during the first few years. Stape et al. [19] studied eucalyptus biomass production in relation to environmental factors such as water use, light supply, and N uptake in Brazil. These authors showed that the supply of water is likely the most limiting factor in fertilized plantations.

Simulation models have been developed to predict tree transpiration, soil water movement, nutrient transport, and biomass production. Landsberg and Waring [20] applied the 3-PG (Physiological Principles in Predicting Growth) model to simulate Sitka spruce (*Picea sitchensis* (Bong.) Carr.) stand productivity using the concepts of radiation-use efficiency, carbon balance, and partitioning. BIOMASS has been used to model growth and production in radiata pine (*Pinus radiata* (D. Don)) and Eucalyptus spp. and was able to predict water use and carbon assimilation of these stands [21]. Corbeels et al. [22] modeled the long-term productivity of eucalyptus plantations under different harvest residue and nitrogen management practices. Their simulations showed that retention of harvest residues and application of N fertilizer is useful for maintaining long-term productivity. Gonzalez-Garcia et al. [23] applied the 3-PG model to estimate the potential productivity of eucalyptus grown for bioenergy in a region of northwest Spain. They found that the 3-PG model can estimate aboveground biomass and water use, and the eucalyptus production is reduced by low summer rainfall and to a lesser extent by low winter temperatures.

In recent years, several modeling studies were performed to predict nutrient uptake and biomass production of eucalyptus [24–26]. Valadao et al. [5] applied nonlinear models to estimate biomass production and nutrient accumulation of a eucalyptus stand in Cerrado dystrophic soil in Brazil. They confirmed that diameter, basal area, and height are the key parameters to predict eucalyptus volume and biomass. However, this modeling approach does not include time-series predictions. In other words, the model cannot predict the changes of biomass production and nutrient accumulation of a eucalyptus stand with time or tree age. In summary, although the aforementioned experimental and modeling studies have provided valuable insights, little effort has been devoted to modeling eucalyptus biomass production as affected by water and N availability in conjunction with time series hydrological processes. Recently, Ouyang et al. [27] developed a STELLA (Structural Thinking and Experiential Learning Laboratory with Animation) model to estimate water use and N uptake in a mature cottonwood plantation using an hourly time step. The model consists of water dynamics including surface runoff, rainfall/irrigation, evaporation, percolation, and water uptake by roots in the transpiration stream, as well as N dynamics including mineralization, nitrification, denitrification, sorption, leaching, volatilization, uptake, and fertilizer application. Although the model provides a practical tool to estimate water and N dynamics in a mature woody crop plantation, biomass production and its relationship to water use and N uptake during the juvenile growth stage of a tree plantation system have not been included in the model.

The purpose of this study is to modify the cottonwood model developed by Ouyang et al. [27] for simultaneously estimating soil hydrological processes, nitrogen (N) uptake, and biomass production in a eucalyptus (*E. grandis* × *urophylla*) plantation. More specifically, our objectives were to: (1) modify the STELLA model [27] to incorporate the eucalyptus biomass production component and its response to water use, N uptake, and stand age; (2) calibrate and validate the model using experimental data; and (3) apply the

model to assess eucalyptus annual net primary production (ANPP) and woody biomass production (WBP), as well as their relationships to water use and N uptake during the entire cultivation period.

2. Materials and Methods

2.1. Model Description

A conceptual diagram showing the dynamics of water and N in a growing eucalyptus plantation is shown in Figure 1, which is modified from Ouyang et al. [27]. Since the mathematical functions for soil water dynamics in a eucalyptus plantation have been published in Ouyang et al. [28] and the mathematical functions for N dynamics are very similar to those in other short-rotation woody crop plantations that have been published by Ouyang et al. [27], an elaborate description of these functions is beyond the scope of this study. However, the mechanisms for eucalyptus N uptake and biomass production in a growing plantation are not included in Ouyang et al. [27,28]. It is, therefore, necessary to incorporate these mechanisms into the model.

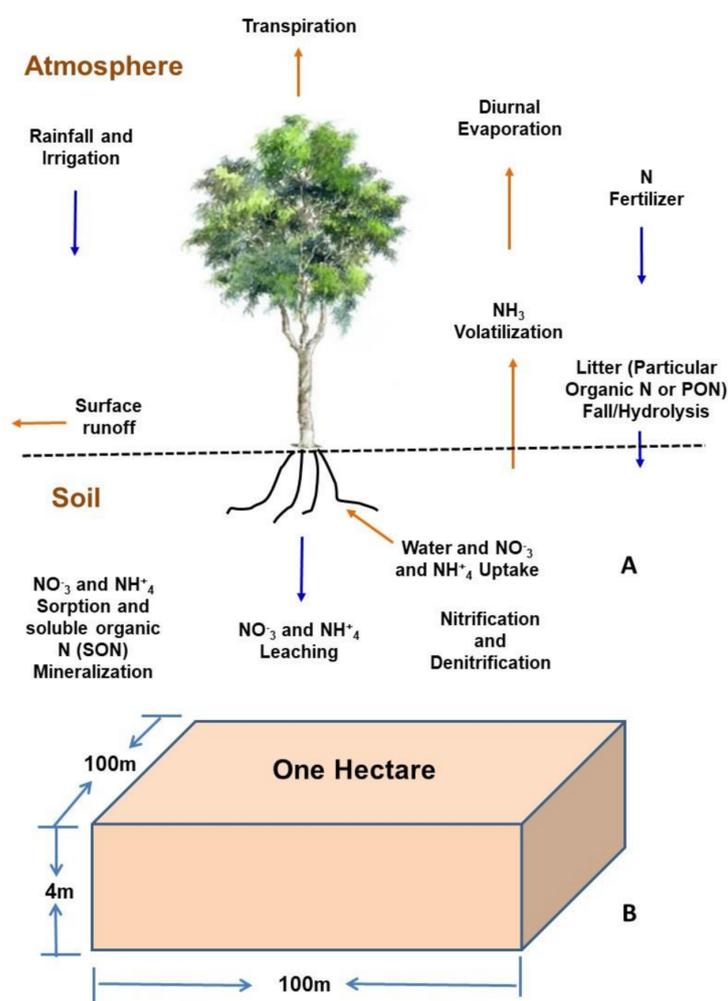


Figure 1. Schematic diagram showing the water and N dynamics in a growing-eucalyptus plantation (A) with the modeled domain used in this study (B). The diagram is modified from Ouyang et al. [27].

Leaf water transpiration depends on daily weather conditions, age of tree species, and soil water availability. Morris et al. [13] investigated water use by *Eucalyptus urophylla* plantations in South China and from their experimental data, we found that the relationship

between the leaf water transpiration and the growing time (annual growing cycle) of the eucalyptus followed the polynomial function:

$$E_{\text{leaf}} = a_1 t^3 - a_2 t^2 + a_3 t + a_4 \quad (1)$$

where E_{leaf} is the leaf water transpiration (cm/h), t is the annual time (h), and a_1 through a_4 are the coefficients (dimensionless).

Using the above polynomial function and adapting to account for diurnal and age variations, we obtained the following equation for leaf water transpiration during eucalyptus growth:

$$E_{\text{leaf}} = (a_1 t^3 - a_2 t^2 + a_3 t + a_4) f_{\text{diurnal}} f_{\text{age}} \quad (2)$$

where f_{diurnal} is the diurnal factor (dimensionless) and f_{age} is the age factor (dimensionless).

For typical weather conditions, transpiration ceases at night due to stomata closure and resumes at dawn [29]. The diurnal factor in Equation (2) is introduced to reflect this daily variation and is given as [27]:

$$f_{\text{diurnal}} = b_1 \exp\left(-b_2 \left(\frac{t - b_3}{b_4}\right)^2\right) \quad (3)$$

where b_1 to b_4 are the constants for characterizing the diurnal factor.

The tree age factor in Equation (2) is introduced to account for variations of leaf water transpiration during eucalyptus growth and is given as:

$$f_{\text{age}} = \frac{1}{1 + c_1 e^{(-c_2 t)}} \quad (4)$$

where c_1 and c_2 are the constants for characterizing the age factor. Equation (4) is developed based on the data for the tree ages ranged from 1.5 to 26 years reported by Zhang et al. [30].

The input values for the coefficients a_1 through a_4 in Equation (1) were obtained based on the experimental data reported by Morris et al. [13]. The input values for the constants b_1 through b_4 in Equation (3) were obtained based on the study by Ouyang et al. [28]. The input values for the constants c_1 and c_2 in Equation (4) were estimated based on the investigation by Zhang et al. [30]. Zhang et al. [30] investigated the biomass and carbon storage of eucalyptus and acacia in relation to age in the Pearl River Delta, South China. Their published data for eucalyptus biomass production with age were used to calculate the age factor. It is also assumed that leaf water transpiration ceases when the soil water content is less than or equal to the wilting point ($0.16 \text{ cm}^3/\text{cm}^3$ for the sandy clay used in this study) [31], as well as when it is raining. These assumptions are implemented in the STELLA model.

The mathematical functions for root water and N uptakes by eucalyptus are very similar to those of other woody tree species, which have been published in Ouyang et al. [27] and are given below:

$$Q_{\text{root}}^{\text{water}} = Q_{\text{leaf}}^{\text{transp}} / 0.98 \quad (5)$$

$$R_{\text{root}}^{\text{rate}} = Q_{\text{root}}^{\text{water}} C_{\text{soil}} \delta \quad (6)$$

where $Q_{\text{root}}^{\text{water}}$ is the soil water uptake rate (cm^3/h), $Q_{\text{leaf}}^{\text{transp}}$ is the leaf transpiration rate (cm^3/h), $R_{\text{root}}^{\text{rate}}$ is the rate of root uptake (g/h), C_{soil} is the soil N concentration (g/cm^3), and δ is the reflection coefficient that measures the metabolic requirement of N to cross into the root compartment. Details on how Equations (5) and (6) were developed can be found in Ouyang et al. [27].

For a growing-eucalyptus species, the value of the reflection coefficient varies with time and is given as:

$$\delta = \frac{d_1}{[1 + d_2 \exp(d_3 t)]} \quad (7)$$

where d_1 , d_2 , and d_3 are the constants obtained through model calibration (Table 1).

Table 1. Input values for the constants in the equations used in this study.

Equation	Constant	Value	Reference
(1)	a_1	1.2×10^{-9}	Estimated and calibrated based on Morris et al. [13]
(1)	a_2	-3.6×10^{-5}	Estimated and calibrated based on Morris et al. [13]
(1)	a_3	0.24	Estimated and calibrated based on Morris et al. [13]
(1)	a_4	0.0025	Estimated and calibrated based on Morris et al. [13]
(3)	b_1	3.0	Ouyang et al. [27]
(3)	b_2	-0.5	Ouyang et al. [27]
(3)	b_3	12.5	Ouyang et al. [27]
(3)	b_4	2.5	Ouyang et al. [27]
(4)	c_1	9.0	Estimated and calibrated based on Zhang et al. [30]
(4)	c_2	-0.0005	Estimated and calibrated based on Zhang et al. [30]
(7)	d_1	2500	Model calibrated
(7)	d_2	0.01	Model calibrated
(7)	d_3	0.00006	Model calibrated
(8)	e_1	-1.677×10^{-5}	Estimated and calibrated based on Stape et al. [19]
(8)	e_2	0.445	Estimated and calibrated based on Stape et al. [19]
(8)	e_3	3.876×10^{-7}	Estimated and calibrated based on Stape et al. [19]
(9)	f_1	-4.8×10^{-5}	Estimated and calibrated based on Stape et al. [19]
(9)	f_2	1.2	Estimated and calibrated based on Stape et al. [19]
(9)	f_3	4.8×10^{-6}	Estimated and calibrated based on Stape et al. [19]

The aboveground ANPP is used to describe the eucalyptus biomass production, which is estimated as the sum of the woody biomass production plus branch and foliage litterfall for the year when the biomass sampling is performed. The net primary production (NPP) depends on soil water availability, N uptake, and the age of the eucalyptus. For estimating the hourly NPP (kg/ha/h), the following equation is used:

$$\text{NPP} = e_1 t + e_2 N_{\text{uptake}} + e_3 Q_{\text{root}}^{\text{transp}} \quad (8)$$

where N_{uptake} is the N uptake (g/ha/h) and e_1 , e_2 , and e_3 are the coefficients.

The WBP is the net increment in woody biomass during the year. For estimating the hourly WBP (kg/ha/h), the following equation is used:

$$\text{WBP} = f_1 t + f_2 N_{\text{uptake}} + f_3 Q_{\text{root}}^{\text{transp}} \quad (9)$$

where f_1 , f_2 , and f_3 are the coefficients. The input values for the coefficients e_1 through e_4 in Equation (8) and f_1 through f_3 in Equation (9) were estimated and calibrated based on the study reported by Stape et al. [19] and are given in Table 1. These authors conducted experiments in north-eastern Brazil, within a 55 km radius of Entre-Rios (11°85' S, 38°07' W). This area is a sub-tropical region with annual mean temperatures of 21 °C and annual mean rainfall of 1600 mm. A set of 21 plantations of various ages were monitored for biomass production in lateritic soil. Water use efficiency, N uptake, and leaf water transpiration in relation to ANPP and WBP of eucalyptus were measured during the experiment.

2.2. STELLA Model

All of the above equations and the associated assumptions, as well as conditions, were incorporated into the STELLA model. STELLA is a computer software program used to develop models for research and education with applications in economics, sciences, and engineering. Detailed descriptions of the STELLA software can be found in Isee Systems (www.iseesystems.com).

Figure 2 shows the STELLA model map developed in this study, which consists of the following three modules: (1) water dynamic; (2) nitrogen dynamic, and (3) biomass production. The water and nitrogen dynamic modules were developed in our previous study [28], while the biomass production module was developed in this study. The STELLA model normally has the following four basic icons (Figure 3): (1) stock (□), the state variables used to calculate the information accumulation in the stock and the flows into and out of the stock; (2) flows (◁→▷), the exchange variables that control the arrival or departure of information between the state variables; (3) converters (○), the auxiliary variables that can be represented by constant values or by values dependent on other variables or functions of various categories; and (4) connectors (↗), which connect among modeling features, variables, and elements. The “cumulative NPP” is the stock that is used to store the net primary biomass production. The amount of biomass in the stock depends on how much biomass flows (“hourly NPP”) into the stock. The flow is calculated by Equation (8), which is embedded into the flow icon (see the equation inside the dashed line). The rates of transpiration and inorganic nitrogen uptake are needed in Equation (8). The equations and conditions for calculating these rates are embedded in the transpiration and inorganic nitrogen uptake converters and are shown inside the dash lines. Similar procedures are used for implementing the water and nitrogen dynamics.

2.3. Model Calibration and Validation

Model calibration is a process of obtaining the best fit between the observed data and predicted results by adjusting the input parameter values within a reasonable range, while model validation is the same process using the calibrated model without making any changes to the input parameter values. In this study, we used the data reported by Stape et al. [19] for model calibration and validation. These authors examined eucalyptus biomass production along with water and N use efficiencies in north-eastern Brazil. There are 14 eucalyptus stands used in their experiments. We used the data from 7 eucalyptus stands for model calibration and the data from another 7 eucalyptus stands for model validation. Three major components, namely the leaf transpiration (water use), N use (uptake), and ANPP, were calibrated and validated in this study. The major input parameter values used in this study are shown in Tables 1 and 2. The rainfall data are estimated based on Stape et al. [19].

Comparisons of the observed and predicted leaf water transpiration, soil N uptake, and ANPP during the model calibration process are shown in Figure 4. The regression equations were $Y_{\text{Prediction}} = 0.974X_{\text{Measurement}}$ with $R^2 = 0.845$, $p < 0.001$, RPD (relative percentage difference) = 11, and NRMSE (normalized root mean square error) = 0.11 for transpiration, $Y_{\text{Prediction}} = 1.104X_{\text{Measurement}}$ with $R^2 = 0.813$, $p < 0.001$, RPD = 16, and NRMSE = 0.181 for N uptake, and $Y_{\text{Prediction}} = 1.104X_{\text{Measurement}}$ with $R^2 = 0.685$, $p < 0.001$, RPD = 23, NRMSE = 0.505 for ANPP. The RPD is the absolute value of the difference between each method prediction and each field measurement, divided by field measurement and multiplied by 100. The median RPD is then used for comparison between the method predictions and the field measurements [32,33]. With very good R^2 , low p values, and reasonable RPD and NRMSE, we concluded that the STELLA model developed in this study performed well for predicting water use, N uptake, and biomass production in the eucalyptus plantation.

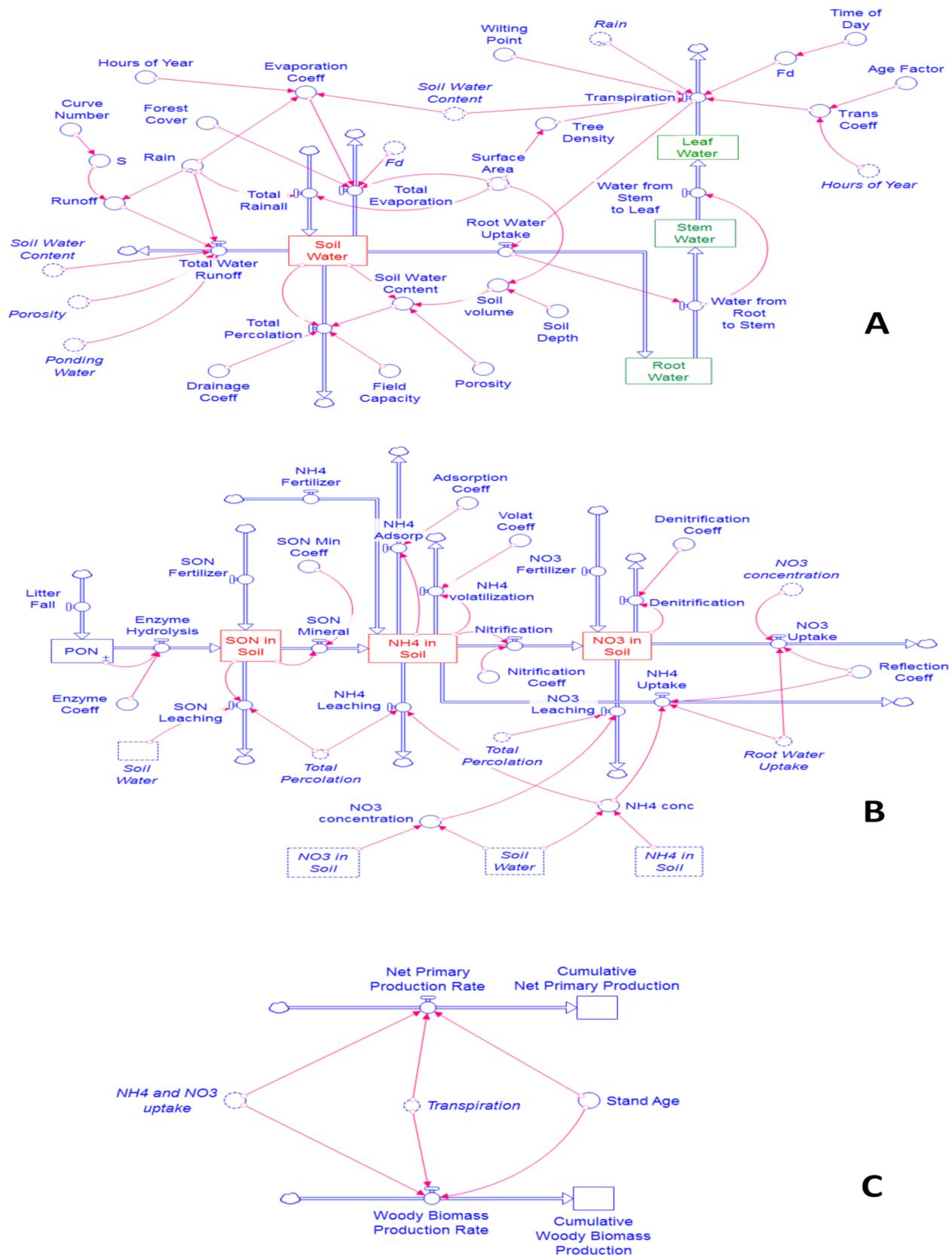


Figure 2. A general STELLA model map showing soil water dynamics (A), N dynamics (B), and biomass production (C).

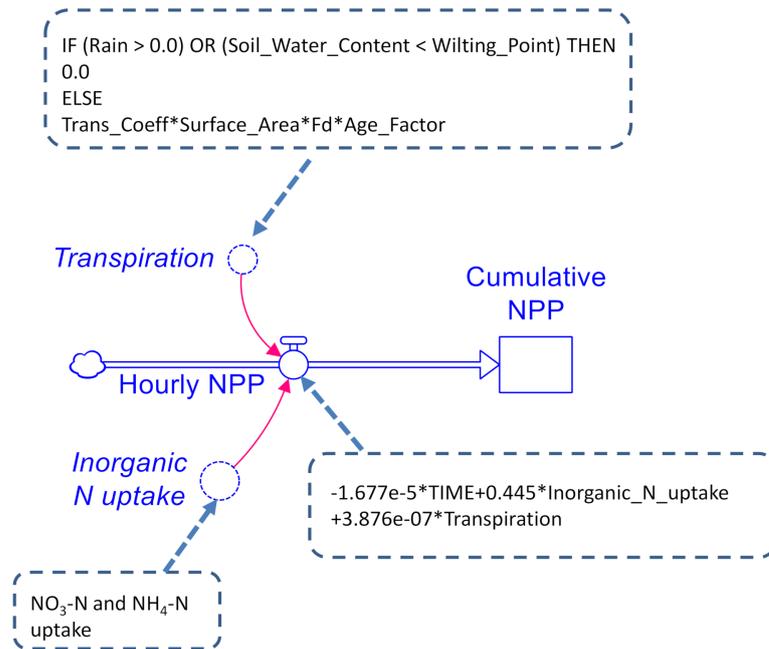


Figure 3. A detailed explanation of the STELLA model.

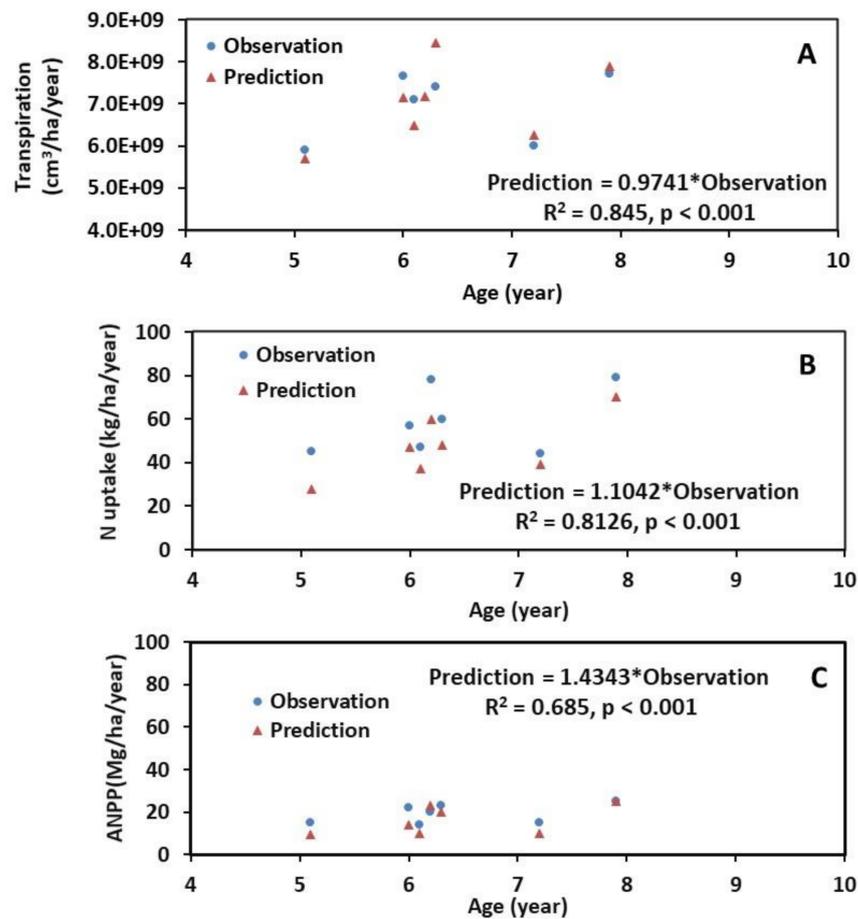


Figure 4. Comparison of model-predicted and field measured transpiration (A), N uptake (B), and ANPP (C) during the model calibration.

Table 2. Input parameter values used for model validation and application.

Parameter	Value	Source
Soil Water		
Curve number	38	Nearing et al. [34]
Rainfall (cm/h)	Time series measurements	Ouyang et al. [28]
Plantation area (cm ²)	$1.0 \times 10^{+9}$	Assumed
Soil depth (cm)	400	Ouyang et al. [28]
Soil porosity (cm ³ /cm ³)	0.35	Ouyang et al. [28]
Field capacity (cm ³ /cm ³)	0.31	Hillel, 1982 [32]
Wilting point	0.16	Ouyang et al. [29]
Percolation coefficient (1/h)	0.125	Ouyang et al. [29]
Initial soil water content (cm ³ /cm ³)	0.25	Assumed
Soil evaporation rate (cm ³ /cm ² /h)	$-10^{-14}t^3 + 3 \times 10^{-11}t^2 + 6 \times 10^{-07}t + 0.0005$	Ouyang et al. [29]
Initial soil water storage (cm ³)	$1.2 \times 10^{+11}$	Calculated based on initial soil water content
Nitrogen		
Initial dissolved SON (g/ha)	31,200	Ouyang et al. [29]
SON mineralization rate	0.005	Ouyang et al. [29]
Initial dissolved NH ₄ (g/ha)	7500	Ouyang et al. [29]
Initial dissolved NO ₃ (g/ha)	1500	Ouyang et al. [29]
NH ₄ nitrification rate (1/h)	0.3	Ouyang et al. [29]
NH ₄ volatilization rate (1/h)	0.00015	Ouyang et al. [29]
NH ₄ adsorption rate (1/h)	0.0005	Ouyang et al. [29]
NO ₃ denitrification (1/h)	0.005	Ouyang et al. [29]
Litter enzyme hydrolysis rate	1.00×10^{-6}	Ouyang et al. [29]
Application of N fertilizers	None	
Eucalyptus		
Initial root water (cm ³ /ha)	359,618,230.9	Ouyang et al. [29]
Initial stem water (cm ³ /ha)	1,027,480,660	Ouyang et al. [29]
Initial leaf water (cm ³ /ha)	1,027,480,660	Ouyang et al. [29]
Canopy transpiration (cm ³ /cm ² /h)	$2 \times 10^{-14}t^3 - 6 \times 10^{-10}t^2 + 4 \times 10^{-6}t + 0.0025$	Ouyang et al. [29]
Forest cover factor	0.85	Assumed
Reflection coefficient	0.001	Calibrated based on Nobel [30]
Diurnal factor	$3\exp(-0.5((t - 12.5)/2.5)^2)$	Ouyang et al. [29]
Litter fall (1/h)	0.0006t	Estimated from Zhang et al. [31]

Comparisons of the observed and predicted leaf water transpiration, soil N uptake, and ANPP during the model validation process are shown in Figure 5. The values of R² ranged from 0.760 to 0.995 with all of the *p* values <0.001. These statistical measures indicated that model predictions matched the field observations reasonably well during the model validation process.

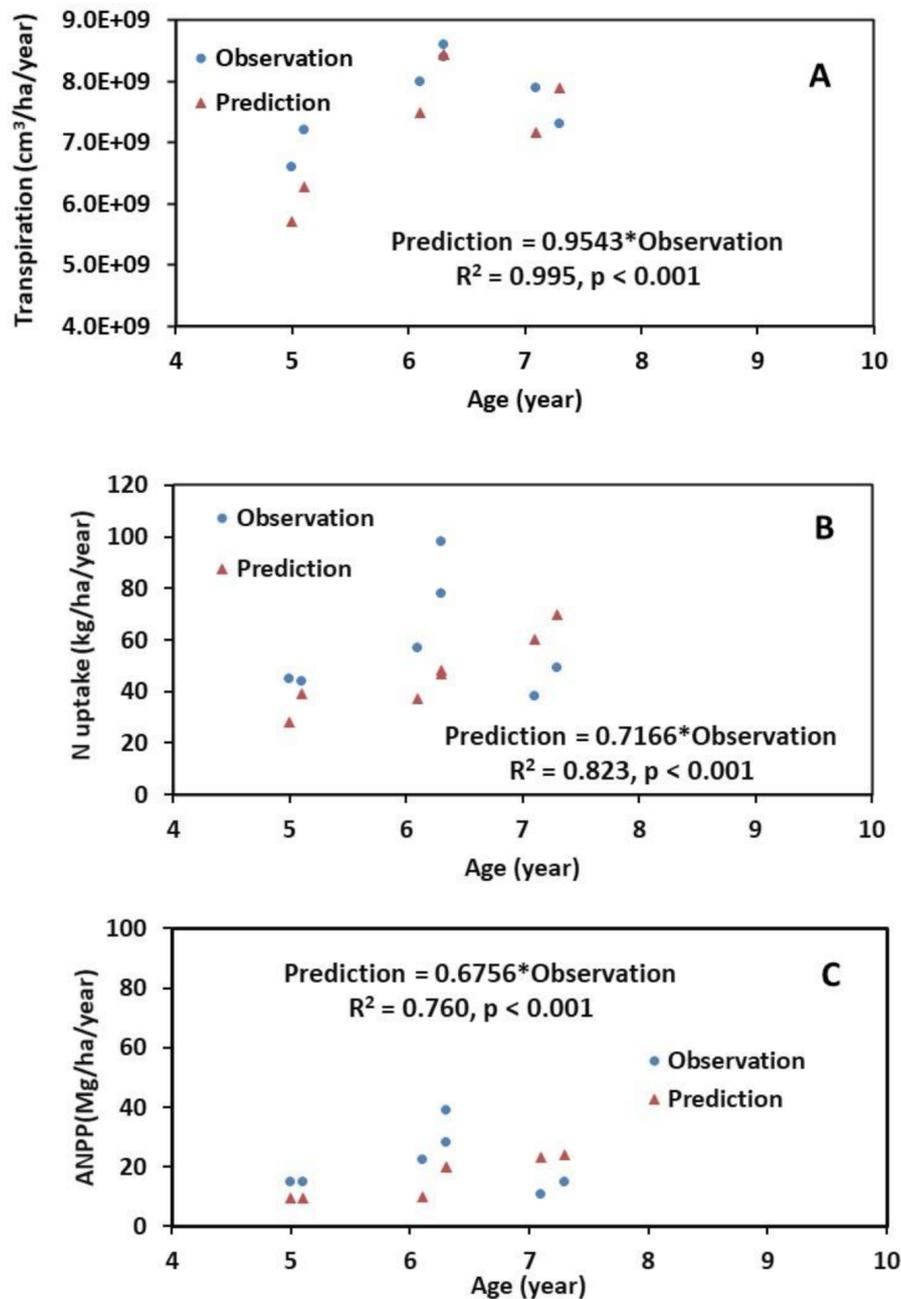


Figure 5. Comparison of model-predicted and field measured transpiration (A), N uptake (B), and ANPP (C) during the model validation.

2.4. Model Scenario

A simulation scenario was developed to quantify the relationships of eucalyptus biomass production to its age, water use, and N uptake for a simulation period of 20 years. A hypothetical modeled domain with an area of one hectare and a depth of 4 m grown with eucalyptus seedlings in sandy clay soil was selected for the simulation scenario (Figure 1). This scenario had similar climate and soil conditions as reported by Stape et al. [19]. In other words, the major input parameter values used for the scenario were the same as those during the model validation. The model had an hourly time step and the simulation started at zero hour of the first day of January in the 1st year and terminated at the end of December in the 20th year.

3. Results and Discussion

3.1. Annual Variations of Water Use, N Uptake, and NPP

Annual variations of daily eucalyptus water use (transpiration), N uptake, and NPP over a 20-year simulation period are shown in Figure 6. A typical annual water use pattern, with increasing use from spring to fall followed by decreasing use from fall to winter, was observed (Figure 6A). The highest rate of water use was about $4.5 \times 10^5 \text{ cm}^3/\text{ha}/\text{d}$ during winter but was about $8.5 \times 10^6 \text{ cm}^3/\text{ha}/\text{d}$ during summer in 5-year old trees. Such an annual water use pattern occurred because of the annual eucalyptus growing cycle, which normally grows faster from spring to fall and slower (or cessation) from fall to the following winter.

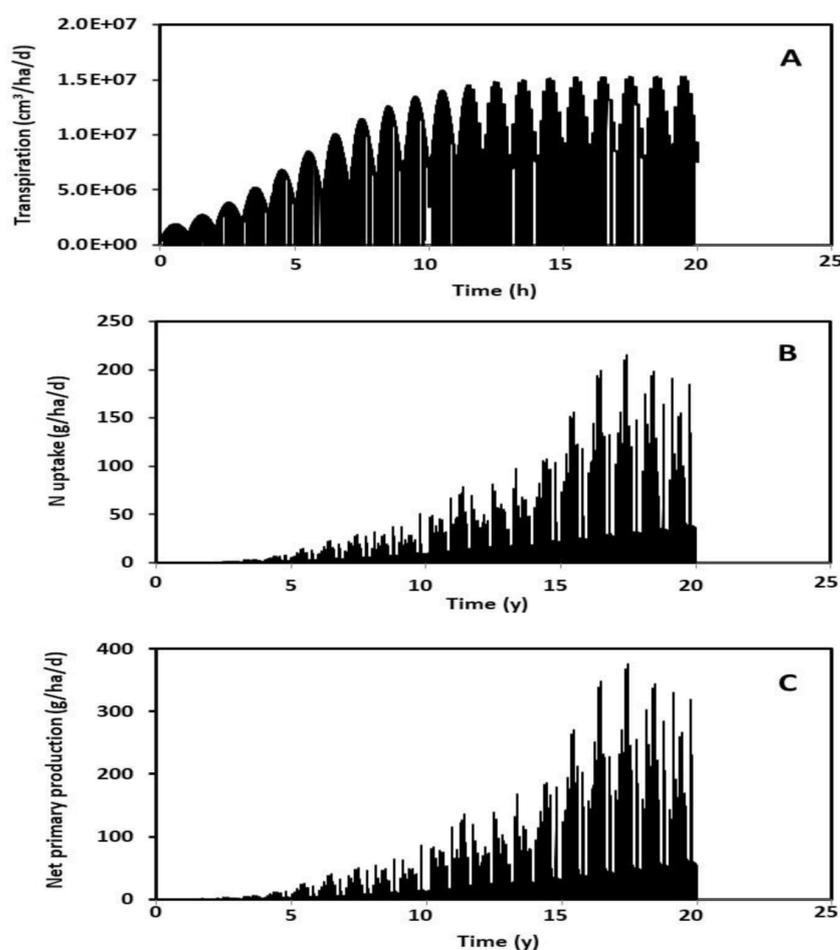


Figure 6. Predicted rates of water use (A), N uptake (B), and NPP (C) during a 20-year simulation period.

Figure 6A further reveals that the overall rate of water use increased from the first year to about 17 years and then reached its equilibrium from 17 to 20 years when the eucalyptus have matured. The highest rate of water use during summer in the mature stage (or after 17 years) was about $1.5 \times 10^7 \text{ cm}^3/\text{ha}/\text{d}$, which was equivalent to 1.5 mm/d. This finding was within the range reported by Ferraz et al. [35]. These authors found the rate of eucalyptus water use ranged from 1.2 to 7.3 mm/d in Brazil.

In general, the annual pattern of daily N uptake was similar to that of annual water use, which increased from spring to fall and then decreased from fall to the following winter due to the annual eucalyptus growing cycle (Figure 6B). For instance, the highest rate of N uptake was 5.5 g/ha/d during winter but was about two times greater at 10.7 g/ha/d during summer in 5-year old trees. However, this pattern was also driven by other factors such as soil N concentration, water content, and root water uptake. As a result, the annual

pattern of N uptake was not as “smooth” as that of water use. Starting from the first year, daily N uptake increased to its maximum of 215 g/ha/d in 17-year old trees then decreased from 17 to 20 years. Guo et al. [18] reported that the total N uptake from a eucalyptus plantation in New Zealand ranged from 136 to 547 g/ha/d. Our prediction was within this range. The increase in N uptake during the growing stage from 0 to 17 years and the decrease in N uptake at the mature age stage from 17 to 20 years occurred because the younger eucalyptus had higher metabolisms and needed a larger quantity of N for growth and the older eucalyptus had lower metabolisms and needed less quantity of N for maintenance [30].

Analogous to the case of N uptake, the annual pattern of daily NPP showed a typical behavior: increasing from spring to fall followed by a decrease from fall to winter (Figure 6C). At the age of 5 years, the highest rate of NPP during winter was about 8.4 kg/ha/d but was about 17.7 kg/ha/d in summer. Similarly, the overall rate of daily NPP increased from the first year and reached its equilibrium at the age of 16 years and then decreased from 17 to 20 years. The average rate of NPP was about 40 kg/ha/d at the age of 6 years. This rate was somewhat close to that reported by Valadao et al. [5]. These authors performed biomass and nutrient estimates in a eucalyptus stand in Cerrado, Brazil, and found that the average rate of biomass production is about 60 kg/ha/d.

3.2. ANPP vs. Water Use

The relationship between ANPP and water use during the entire eucalyptus cultivation period of 20 years is shown in Figure 7A. Two distinct patterns were apparent based on the modeled predictions. During the growth period, from 0 to 17 years, the ANPP increased exponentially with water use. The maximum ANPP was 61,000 kg/ha in 17-year old trees when water use was $3.13 \times 10^3 \text{ m}^3/\text{ha}$. However, during the mature period, from 17 to 20 years, the ANPP decreased slightly with increased water use. These results indicate that water was used more efficiently in eucalyptus during the growth stage (0–17 years) than during the mature stage (17–20 years). He et al. [36] and Drake et al. [37] reported a similar relationship, i.e., a rapid increase of NPP in the young ages of forest type groups, peak growth in the middle ages, and slow decline in the mature ages. This occurred because the young eucalyptus had higher metabolisms than those of the old eucalyptus.

Figure 7B shows water use efficiency (WUE) as a function of eucalyptus age. The WUE was calculated by dividing ANPP with annual water use. The WUE increased with eucalyptus age during the growth stage and decreased slightly during the mature stage (after 17 years). The maximum WUE throughout the modeled period was 18 kg/m³ seen in 17-year old trees. In other words, at their most efficient time, a 1-ha eucalyptus plantation used 1 m³ of water to produce 18 kg of net carbon. In general, the average WUE during the growth stage was about 7.6 kg/m³.

3.3. ANPP vs. N Uptake

Unlike the case of ANPP vs. water use, a linear correlation was found between the ANPP and the N uptake during the entire eucalyptus cultivation period of 20 years (Figure 8A). With a very good R² value, the ANPP could be approximated using the linear relationship with N uptake shown in Figure 8A.

During the mature stage, the annual water use reached an asymptote that was maintained in older trees to meet the needs of leaf water transpiration. In contrast, during the mature stage, N uptake decreased (Figure 6B) because less N was needed to produce ANPP. In other words, the use of N was proportional to the generation of ANPP. Thus, it is much easier to estimate ANPP using N uptake as opposed to water use because the former had a linear correlation during the entire eucalyptus cultivation period. Stape et al. [19] reported that both the water use and N uptake have linear correlations with the ANPP. However, their results are based on data collected during the eucalyptus growth stage.

Similar to WUE, N use efficiency (NUE) increased during the growth stage and decreased slightly during the mature stage (Figure 8B). The NUE was calculated by dividing

the ANPP with annual N uptake. Maximum NUE was about 1200 kg/kg in 17-year old trees meaning that, under optimal NUE, every 1 kg of N used by eucalyptus could produce 1200 kg of NPP. Overall, the average NUE during the growth stage was 700 kg/kg.

3.4. Woody Biomass Production

Comparison of cumulative WBP, cumulative water use, and cumulative N uptake of eucalyptus during the growing stage for 17 years is shown in Figure 8C. This figure demonstrates that to harvest 348,000 kg woody biomass, it required 39,963 m³ of water and 321 kg of N. Assuming the density of water is close to 1000 kg/m³, to produce 1000 kg of woody biomass, the eucalyptus needs about 114.84 m³ of water and 0.92 kg of N.

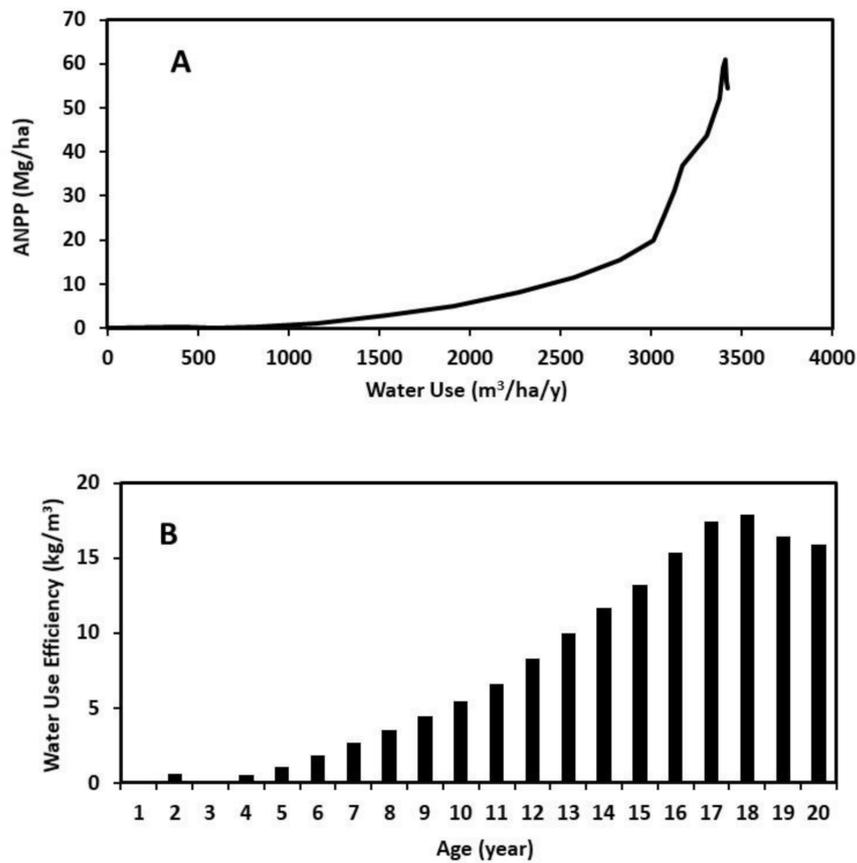


Figure 7. ANPP as a function of water use (A) and WUE as a function of eucalyptus age (B).

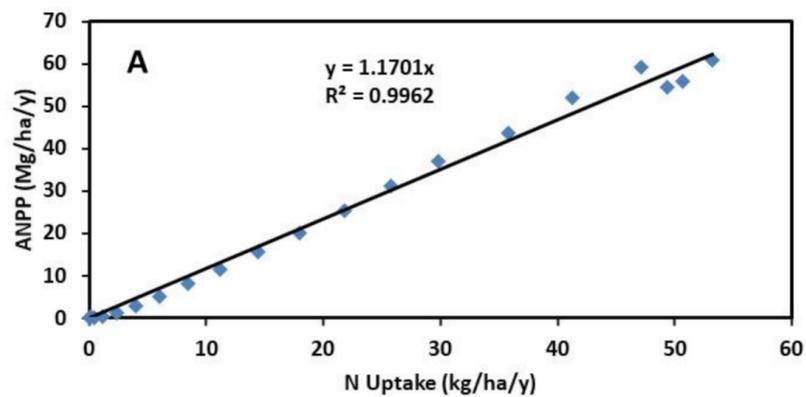


Figure 8. Cont.

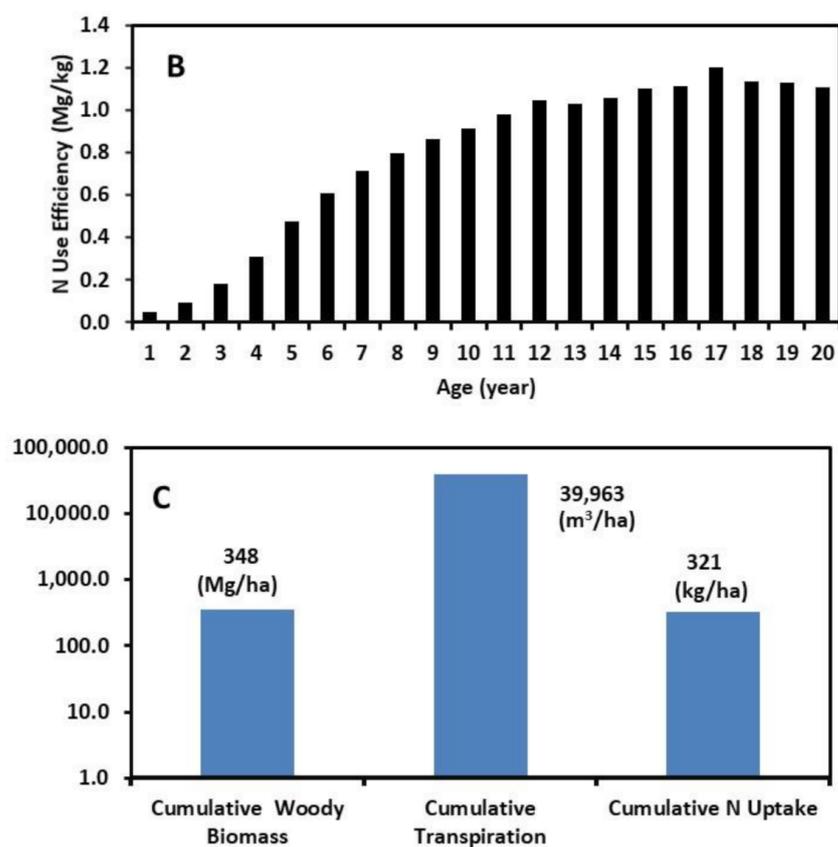


Figure 8. ANPP as a function of N uptake (A); NUE as a function of eucalyptus age (B); and comparison of cumulative woody biomass, water use (transpiration), and N uptake for a simulation period of 17 years during the eucalyptus growing stage (C).

4. Conclusions

A STELLA model was developed to assess eucalyptus biomass production, water use, and N uptake, as well as their relationships. The model was calibrated and validated with good agreements between the model predictions and the field measurements. A simulation scenario was then chosen to assess eucalyptus ANPP and WBP, as well as their relationships to WUE and NUE during the entire cultivation period of 20 years.

Two distinct patterns were found: (1) during the growing stage, water use, N uptake, and ANPP increased exponential with eucalyptus age, and (2) during the mature stage, water use approached an equilibrium condition with eucalyptus age, whereas the N uptake and ANPP decreased slightly with eucalyptus age.

ANPP increased exponentially with water use during the growing stage but decreased slightly with water use during the mature stage. A similar trend was found for WUE. Results indicated that water was used more efficiently per unit ANPP during the growing stage in the eucalyptus.

Unlike the case between the ANPP and water use, a linear correlation was found between the ANPP and N uptake during the entire eucalyptus cultivation period. Thus, it is easier to estimate ANPP given N uptake than water use because the former had a linear correlation during the entire eucalyptus cultivation period.

All simulation results compared well with the literature reported values, which confirmed that the STELLA model developed here is capable of predicting WUE, NUE, ANPP, and WBP in eucalyptus plantations, as well as in other tree plantations after some model modifications.

It should be noted that although the simulations were performed in sandy clay soil in this study, the STELLA-based model can be easily extended to other types of soils.

Additionally, the model did not include the impacts of biotic and abiotic stresses on eucalyptus growth as we focused on the average annual conditions. Nonetheless, further study is warranted to include these mechanisms.

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