



A system dynamic model to estimate hydrological processes and water use in a eucalypt plantation



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ABSTRACT

Eucalypts have been identified as one of the best feedstocks for bioenergy production due to their fast-growth rate and coppicing ability. However, their water use efficiency along with the adverse environmental impacts is still a controversial issue. In this study, a system dynamic model was developed to estimate the hydrological processes and water use in a eucalyptus *urophylla* plantation using the STELLA (Structural Thinking and Experiential Learning Laboratory with Animation) software. This model was both calibrated and validated with very good agreements between model predictions and field measurements obtained from our experiment. Two simulation scenarios were employed in this study, one was to quantify the hydrological processes in a eucalypt plantation (40 m × 40 m) under a normal (a base scenario) sandy soil condition, while the other was to estimate the potential impacts of the wet and dry sandy soil conditions upon the eucalyptus water use. A characteristic monthly variation pattern was found for soil evaporation, leaf transpiration, and root uptake, with increasing from winter to summer and decreasing from summer to the following winter. Overall, the rates of evaporation, transpiration, evapotranspiration (ET), and uptake were in the following order: ET > root uptake > leaf transpiration > soil evaporation. The maximum rate of leaf transpiration was about five times greater than that of soil evaporation. The cumulative annual water use by the eucalypts was 690,000 L/plot (or 3200 L/tree). Although no differences in ET rate and water use were found between the base and wet soil conditions, the discernable discrepancies in ET rate and water use were observed between the wet and dry soil conditions when the soil water content was below 0.17 cm³/cm³. This study suggests that the system dynamic model developed with STELLA is a useful tool to estimate soil hydrological processes and water use in a eucalypt plantation.

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1. Introduction

In recognition of the depletion of fossil fuels within the next few decades and in view of the current concerns on global climate change due to the consumption of fossil fuels, tremendous efforts have been devoted in recent years to utilizing biomass as an alternative biofuel with promising results (Berndes et al., 2003; IEA, 2011; Hauk et al., 2014). Biomass, the most common form of renewable energy, is a biological material derived from algae, agronomic crops, grasses, trees, and municipal waste. Biomass has the potential to become a major global energy source in the next century (Hall, 1997; Kartha and Larson, 2000; Hauk et al., 2014). Increasing future demand for biomass is likely to include the use of fast-growing hardwoods produced in short-rotation woody crop

plantations. Woody crops can yield energy through the conversion of their biomass into convenient solid, liquid or gaseous fuels for industrial, commercial, and domestic uses. IEA Bioenergy (2002) estimated that biomass provides about 11% of the world's primary energy supply, and about 55% of the four billion cubic meters of wood used annually by the world's population is used directly as fuel wood or charcoal to meet daily energy needs for heating and cooking. Balat and Ayar (2005) reported that world production of biomass is about 146 billion metric tons a year, mostly with wild plants, and biomass accounts for 35% of primary energy consumption in developing countries. Overall, the renewable energy sources such as solar, wind, and biomass contribute 19% of the global final energy consumption, half of which is supplied by biomass (REN21(Ed.), 2013).

Over the past several decades, short-rotation (3–15 years) techniques and tree improvement methods have been applied to species such as poplar (*Populus* spp.), willow (*Salix* spp.), and eucalyptus species (e.g., *Eucalyptus globulus*) to identify clones selected

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for their rapid growth, tolerance to pests, and suitability to site conditions to improve biomass production (Volk et al., 1999; Coleman and Stanturf, 2006; Zalesny et al., 2007; Kline and Coleman, 2010; Stanturf et al., 2013). Eucalyptus, native to Australia and Indonesia, is among the fastest growing hardwood genus and is planted in many parts of the world such as India, South Africa, south China and southeast USA (Bai and Gan, 1996; Dye, 1996; Morris et al., 2004; Gonzalez et al., 2011; Albaugh et al., 2013; Callahan et al., 2013; Stanturf et al., 2013). Eucalyptus species can accumulate as much as 40 metric tons of dry matter per hectare per year on a wide range of sites in a tropical region (Sachs et al., 1980; Albaugh et al., 2013). These fast-growing tree species can produce biomass for pulp and paper, charcoal, and solid wood products. Given their fast growth rate and coppicing ability, eucalypts have also been identified as potential feedstocks for lignocellulosic biofuels.

There are, however, concerns about eucalypts water consumption and their potential adverse environmental impacts from many countries around the world (Dye, 1987; Olbrich et al., 1993; Soares and Almeida, 2001; Albaugh et al., 2013). Van Lill et al. (1980) performed a paired catchment experiment with eucalypts (*Eucalyptus grandis*) versus natural grass cover on the eastern escarpment of South Africa. These authors found that afforestation with *E. grandis* exerts an observable influence from the third year after planting, with a maximum reduction in stream flow ranged from 300 to 380 mm y⁻¹. Scott and Lesch (1997) showed that eucalypts cause 90 to 100% reduction in stream flow, while pines result in only 40–60% reduction in stream flow in the first eight years or so after treatment. However, these differences may diminish as the pine stands become well-established. Studies from India (Calder et al., 1992) and South Africa (Dye, 1996) showed that when water resources are limited, the area, location and management of eucalypt plantations need to be carefully considered to avoid conflict with other water users. Morris et al. (2004) studied water use by eucalyptus plantations in southern China. Their results suggest that annual water use by the eucalypt plantations is about 550 mm and potential annual water use without limiting soil water available is about 865 mm. Other studies stated that well-managed eucalypt plantations are beneficial rather than detrimental to the water use and environment (Poore and Fries, 1985; White et al., 1995; Casson, 1997). Although the above and other studies, including Australia (Morris and Collopy, 1999), Brazil (Soares and Almeida, 2001), Portugal (Osorio et al., 1998), South Africa (Le Maitre et al., 2002), south China (Lane et al., 2004; Morris et al., 2004), India (Kallarackal and Somen, 1997) and Pakistan (Mahmood et al., 2001), have provided valuable insights into our understanding of the eucalypt plantations, the water dynamics associated with possible adverse environmental impacts in the eucalypt plantation ecosystems are still poorly understood. A more complete knowledge of these dynamics and possible impacts is essential to effective application of the eucalyptus biomass production technique. Since the soil hydrological processes and water use in the eucalypt plantation are very complex, it is very difficult to quantify them by experimentation alone for a variety of eucalyptus species, for different soil and hydrological conditions, and for all possible combinations of surficial driving forces. Therefore, computer models are essential to circumvent these obstacles.

Several simulation models have been developed to predict tree transpiration, soil water movement, nutrient transport, carbon balance, and biomass production. Running and Coughlan (1988) applied the FOREST-BGC model to simulate the annual hydrological balance and net primary production of a hypothetical forest stand in seven contrasting environments. Landsberg and Waring (1997) applied the 3-PG (Physiological Principles in Predicting Growth) model to simulate forest productivity using the concepts of radiation-use efficiency, carbon balance, and partitioning. The 3-PG model has been used to predict environmental

limitations on growth and final yield of Sitka spruce (*Picea sitchensis*) stands (Waring, 2000). McMurtrie et al. (1990) developed the processed-based BIOMASS model to describe canopy net assimilation, biomass production, and water use of forest stands in relation to weather, tree nutrition, canopy architecture, soil physical characteristics, and physiological variables. BIOMASS has been used to model growth and production in radiata pine (*Pinus radiata*) and *Eucalyptus* spp., and was able to predict water use and carbon assimilation of stands. Williams et al. (1996) developed a soil–plant–atmosphere (SPA) model to simulate ecosystem photosynthesis and water balance at fine temporal and spatial scales. SPA has been employed to diagnose eddy flux data and is a tool for scaling up leaf level processes to canopy and landscape processes. More specifically, Soares and Almeida (2001) developed a five-layered water balance model with water movement between soil layers along hydraulic gradients for a eucalypt plantation (*E. grandis* Hill ex. *Maiden hybrids*) in Brazil. Transpiration in the model is calculated using Penman–Monteith equation along with canopy conductance and soil water movement is included in the model. Overall, the aforementioned models are essential research tools and have improved our understanding of forest water balance and biomass production. However, they have been criticized for being too abstract and difficult to understand, use and apply, for requiring too much input data and time entering data, and for requiring advanced training in computers and tree physiology measurements, thereby rendering them impractical for wide use by field-based managers and practitioners (Tharakan et al., 2000). Therefore, a need exists to develop a simple and yet realistic model for this use.

The goal of this study was to develop a STELLA model to quantify the hydrological processes and water consumption in a eucalypt plantation. Specific objectives were to: (1) develop a model component for hydrological processes, including surface runoff, rainfall, infiltration, evaporation, and percolation; (2) develop a model component for water uptake by roots and its upward movement from roots through stems to leaves for transpiration in the xylem system of a eucalyptus; (3) calibrate the STELLA model using our experimental data; and (4) apply the model to estimate hydrological processes and water use in a eucalypt plantation in southern China as a case study.

2. Materials and methods

2.1. Model development

A conceptual diagram emulating the hydrological processes and root water uptake and upward movement in a soil–tree–atmosphere continuum for a eucalypt plantation is shown in Fig. 1. Development of the STELLA model is based on the processes presented in this figure. The modeled domain used in this study was 1600 m² with a soil depth of 400 cm although it could be any dimension. This domain was chosen based on our eucalyptus experimental plot where the experimental data were used for model calibration and validation. Detailed model development steps are given below.

The surface runoff is estimated using the USDA curve number method as follows (USDA-SCS, 1973; Mullins et al., 1993):

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

where R is the surface runoff (cm³/h), P is the rainfall rate (cm³/h) and S , the watershed retention parameter, is estimated by

$$S = \frac{1000}{CN} - 10 \quad (2)$$

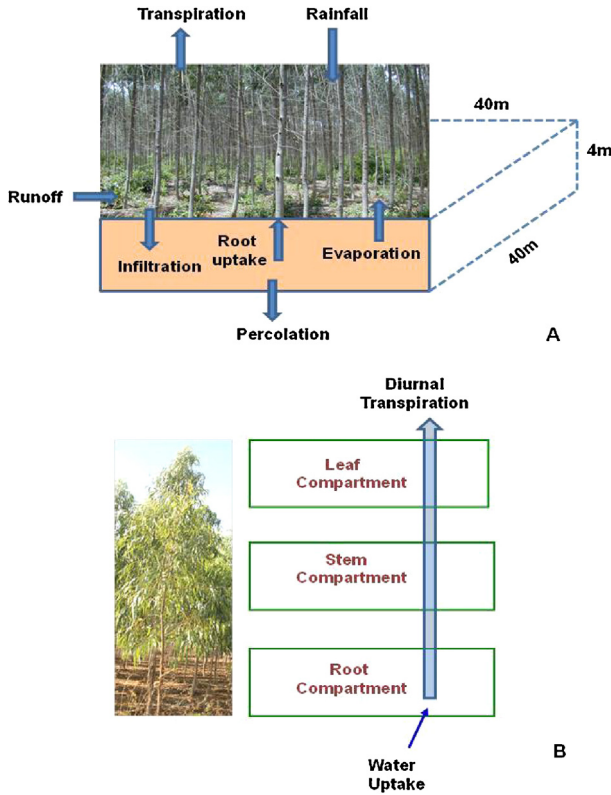


Fig. 1. Schematic diagram showing the hydrological processes in a eucalypt plantation with modeled domain used in this study (A) and a compartmental model for water movement within a eucalypt system (B).

where CN is the runoff curve number. Curve numbers are a function of soil type, soil physical properties, crop type, and management practices. It is also assumed that surface water runoff occurs when the rainfall rate exceeds the infiltration capacity of a soil and the surface water ponding takes place. Surface water runoff rates can also be measured experimentally.

The soil water percolation rate is estimated by the following equation (Mullins et al., 1993):

$$D_{\text{percolation}} = \alpha (\theta - f_c) \quad (3)$$

where $D_{\text{percolation}}$ is the percolation rate (cm^3/h), α is the percolation rate 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). Percolation occurs only when the soil water content is greater than field capacity. Rainfall data can be obtained from local weather stations. It is legitimated to assume that except for surface runoff and evaporation, all of the rain waters are eventually infiltrated into the soil.

Evaporation from soil can be estimated by the Penman–Monteith and Priestley–Taylor equations or pan evaporation methods. In this study, the following empirical equation based on our experimental data is employed to estimate soil evaporation during an annual cycle (Fig. 2A):

$$E_{\text{soil}} = (-1 \times 10^{-14}t^3 + 3 \times 10^{-11}t^2 + 6 \times 10^{-7}t + 0.0005)f_d \times (R^2 = 0.7117) \quad (4)$$

where E_{soil} is the soil evaporation rate (cm^3/h), t is the time (h) starting in January and ending in December, and f_d is a diurnal factor characterizing daily soil evaporation cycle and is given as

$$f_d = \beta \exp \left[-\frac{1}{2} \left(\frac{t - 12.5}{2.5} \right)^2 \right] \quad (5)$$

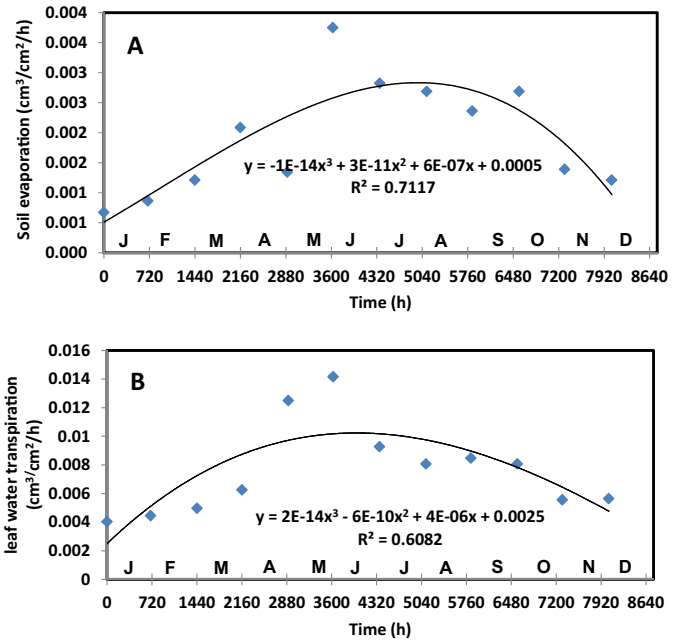


Fig. 2. Empirical equations used for soil evaporation (A) and leaf transpiration (B) calculations in the system dynamic model. These equations were formulated based on our experimental data.

where β is the coefficient obtained through the model calibration (Table 1). Under a normal weather condition, soil evaporation becomes trivial at night and increases from sunrise to noon and decreases from noon to sunset. The diurnal factor (f_d) is introduced to reflect this variation.

Trees are complicated geometrically, physiologically, and biologically. Traditionally, root water uptake and leaf water transpiration can be estimated using plant water potential theory. Ouyang (2008) applied this theory by dividing a generic tree into three compartments of similar structure and function, namely the root, stem, and leaf compartment. The compartments are chosen to account for important processes including water movement and solute transport from the soil to the atmosphere through the roots, stems, and leaves. Each compartment is a transport unit. The water uptake by roots from soil and upward movement from roots to leaves through stems in a tree species is calculated using water potential gradient, contact area, and water conductance between two adjacent compartments (Ouyang, 2008). Although this approach provides a valuable and unique means to characterize water movement and solute transport in the xylem system of a tree, the input data for water potential, contact area, and conductance for the root, stem, and leaf compartments may sometimes be difficult to obtain. To circumvent these obstacles, a simple approach is used to characterize root water uptake and leaf water transpiration in this study as described below.

Leaf water transpiration into the surrounding atmosphere depends on tree species and ambient atmospheric conditions such as vapor pressure, relative humidity, air temperature, and rainfall. It can be estimated through theoretical calculations (Nobel, 1983; Ouyang, 2008) and experimental measurements. In this study, the following empirical equation, which obtained from our annual eucalyptus leaf water transpiration experimental data (Morris et al., 2004), is used to estimate the eucalyptus leaf water transpiration during an annual cycle (Fig. 2B):

$$T_{\text{leaf}} = (2 \times 10^{-14}t^3 - 6 \times 10^{-10}t^2 + 4 \times 10^{-6}t + 0.0025)f_d \times (R^2 = 0.6082) \quad (6)$$

Table 1
Input parameter values used for model calibration and application.

Parameter	Value	Source
Soil		
Curve number	38	Nearing et al. (1996)
Rainfall (cm/h)	Time series measurements	Measured
Plot area (cm ²)	1.60E + 07	Measured
Effective soil area	3.03E + 07	
Soil depth (cm)	400	Measured
Soil porosity (cm ³ /cm ³)	0.38	Measured
Field capacity for sandy soil (cm ³ /cm ³)	0.22	Hillel (1982)
Wilting point	0.16	Measured
Percolation coefficient (1/h)	0.00125	Calibrated
Initial soil water content (cm ³ /cm ³)	0.21	Measured
Soil evaporation rate (cm ³ /cm ² /h)	Eq. (4)	Estimated from experimental data
Initial soil water storage (cm ³)	3.63E + 09	Estimated from experimental data
Diurnal factor parameter β in Eq. (5)	3	Calibrated
Eucalyptus		
Initial root water (cm ³ /plot)	5753,891.694	Estimated from experimental data
Initial stem water (cm ³ /plot)	16,439,690.55	Estimated from experimental data
Initial leaf water (cm ³ /plot)	16,439,690.55	Estimated from experimental data
Canopy transpiration (cm ³ /cm ² /h)	Eq. (6)	Estimated from experimental data

where T_{leaf} is the leaf transpiration rate (cm³/h). For a typical weather condition, transpiration essentially ceases at night due to the stomata closed and commonly starts at dawn because of the stomata opened (Nobel, 1983). The factor (f_d) is introduced to reflect this daily variation. It is also assumed that leaf transpiration ceases when the soil water content is less than or equal to the wilting point as well as during the rain events (Nobel, 1983).

The rate of root water uptake in the soil is primarily controlled by leaf water transpiration. Nobel (1983) stated that about 99% of water taken up by roots is used for transpiration and the remaining 1% is used for tree growth. Therefore, the uptake of soil water by roots is slightly greater than the loss of tree water due to leaf transpiration. Based on our experimental data, we approximated that about 98% of soil water taken up by roots is used for transpiration by the eucalyptus. This approximation was accomplished by water balance calculation using a similar approach reported by Lane et al. (2003). These authors estimated the eucalyptus water balance at the same experimental site as used in this study. Therefore, the rate of soil water uptake by roots can be given as:

$$Q_{\text{root}} = \frac{T_{\text{leaf}}}{0.98} \quad (7)$$

where Q_{root} is the soil water uptake rate by roots (cm³/h).

2.2. System dynamic model

STELLA is a software package for developing system dynamic models by creating a pictorial diagram of a system and then assigning the appropriate values and functions to the system (<http://www.iseesystems.com>). The four major features of the STELLA software are: (1) Stocks, which are the state variables for accumulations and storages, they collect whatever flows into and out of them; (2) Flows, which are the exchange variables that control the arrival or the exchanges of information between the state variables; (3) Converters, which are auxiliary variables, can be represented by constant values or by values dependent on other variables, curves or functions of various categories; and (4) Connectors, which are to connect among modeling features, variables, and elements. System dynamic models with STELLA have been widely used in the biology, economy, ecology, engineer, and environmental sciences (Barlas, 1996; Peterson and Richmond, 1996; Güneralp and Seto, 2008; Forrester, 2007; Ford, 2009; Ouyang et al., 2012, 2015). A detailed description of the STELLA software can be found in Isee Systems (2006).

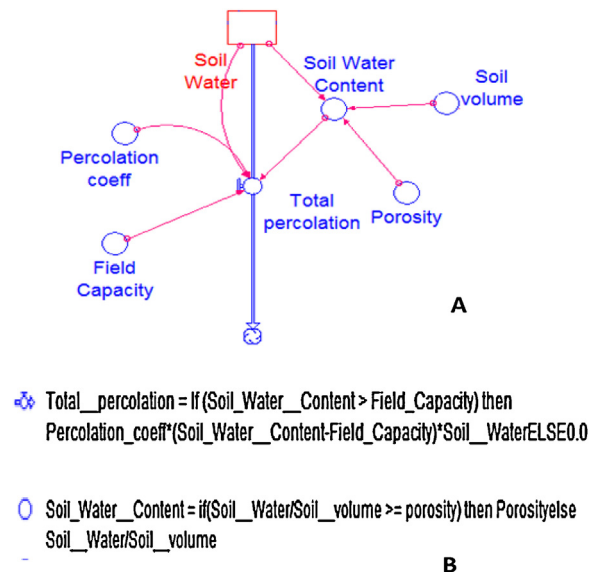


Fig. 3. A schematic diagram showing the translation of soil water percolation process into system dynamic model with STELLA (A) associated program code (B), which was generated automatically by STELLA. This code represented Eq. (3) and conditions for percolation.

Development of a system dynamic model with STELLA begins by drawing a basic structure to capture the conceptual processes described in Fig. 1. For example, the soil water percolation into deeper soil profile or groundwater described by Eq. (3) can be translated into a system dynamic model component as shown in Fig. 3. In this figure, the rectangle is the stock that graphically represents the volume of water stored in the soil. The flow symbol (represented by double lines with arrows and switches) represents the rate that water percolates into the deep soil profile or out of the stock. The other variables are converters (represented by empty circles) that denote the water content, field capacity, and percolation coefficient, soil porosity, and soil volume. These converters are linked together through the use of connectors (represented by single lines with arrows) to calculate soil water content and total percolation. Having developed the basic structure, the second step is to assign the initial values for stocks, equations for flows, and input values for converters. Once the system dynamic model map is created, the model equations will be generated by the STELLA software (Fig. 3B). As shown in this figure, if the soil water

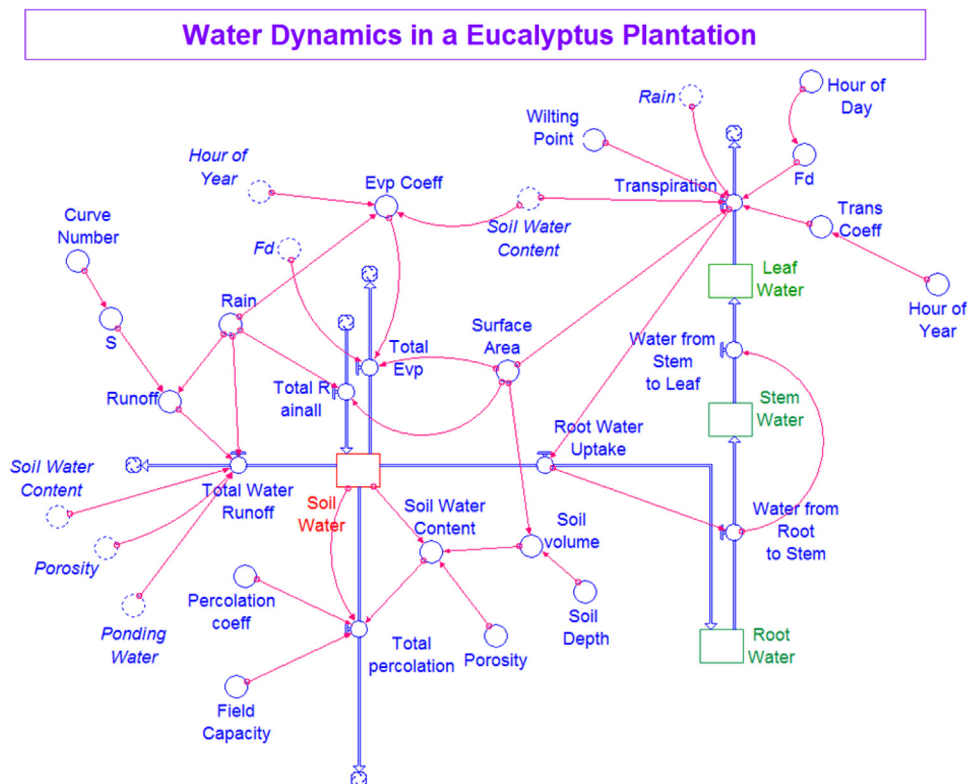


Fig. 4. A system dynamic model with STELLA for simulating hydrological processes and water use in a eucalypt plantation.

content is greater than field capacity, then the total percolation can be estimated by Eq. (3) multiplying by total soil water (in volume), whereas the soil water content is obtained by dividing the total soil water with total soil volume. In the case if the soil is saturated, the soil water content is equal to the soil porosity. Taking the advantage of the STELLA software, there is no need to measure soil water potential or to construct water characteristic curve to calculate the unsaturated soil water content that changes over time. Fig. 4 shows the entire system dynamic model developed with STELLA from this study for hydrological processes and water use in a eucalypt plantation.

2.3. Model calibration and validation

In this study, data used for modeling calibration was from our experiments conducted at the forest farms in Hetou (21°05'N, 109°54'E) within the Nandu River Watershed in Leizhou Peninsula, Guangdong Province, China. This peninsula is a tropical region with monthly mean temperatures of about 28°C in July and 16°C in January. Annual rainfall varies from 1300 mm in the south to 1800 mm in the north of the peninsula. The soil for this site is a sandy soil generated from quaternary sediments with a slope of <1%. The eucalypt plantation was 40 × 40 m and was monitored from September 1999 to January 2002. The leaf water transpiration, soil water evaporation, vapor pressure deficit, eucalyptus biomass production, and certain soil physical properties were measured. Although an elaborate description of the experimental materials and methods is beyond the scope of this modeling study, they can be found in Lane et al. (2004) and Morris et al. (2004).

Before applying the resulted STELLA model to estimate hydrological processes and water use in a eucalypt plantation, the model was calibrated and validated using field measured data. In general, model calibration is a process of obtaining the best fit between the observed data and simulated results by adjusting the input

parameter values, whereas model validation is a process of comparing another set of observed data with the simulation results without adjusting any input parameter value. To reduce the uncertainties of the model predictions, only two input parameters, namely the percolation coefficient (α) in Eq. (3) and diurnal factor coefficient (β) in Eq. (5), were used for model calibration in this study. The calibration was accomplished by adjusting these parameters values to match soil evaporation, leaf transpiration, and soil water content from model predictions with those from experimental measurements. Table 1 lists all of the input parameters values used for model calibration.

Comparisons of the observed and predicted leaf water transpiration, soil water evaporation, and soil water content during model calibration process are shown in Fig. 5. The regression equations were $Y_{\text{Prediction}} = 1.202X_{\text{Measurement}}$ with $R^2 = 0.8963$ for transpiration, $Y_{\text{Prediction}} = 0.8458X_{\text{Measurement}}$ with $R^2 = 0.8676$ for evaporation, and $Y_{\text{Prediction}} = 1.0331X_{\text{Measurement}}$ with $R^2 = 0.6935$ for water content. These represent very good correlations between the model predictions and the experimental measurements. Comparisons of the observed and predicted leaf water transpiration, soil water evaporation, and soil water content during model validation process are shown in Fig. 6. With very good R^2 values and low p values, we concluded that the STELLA model developed in this study performed well in predicting hydrological processes in the eucalypt plantation.

3. Model applications

Two simulation scenarios were performed in this study. The first scenario (base scenario) was chosen to quantify soil hydrological processes such as evaporation, runoff, percolation, and water content as well as to estimate eucalyptus water dynamics such as root water uptake, leaf water transpiration, and cumulative water use under a normal soil condition for a simulation period of one year. In

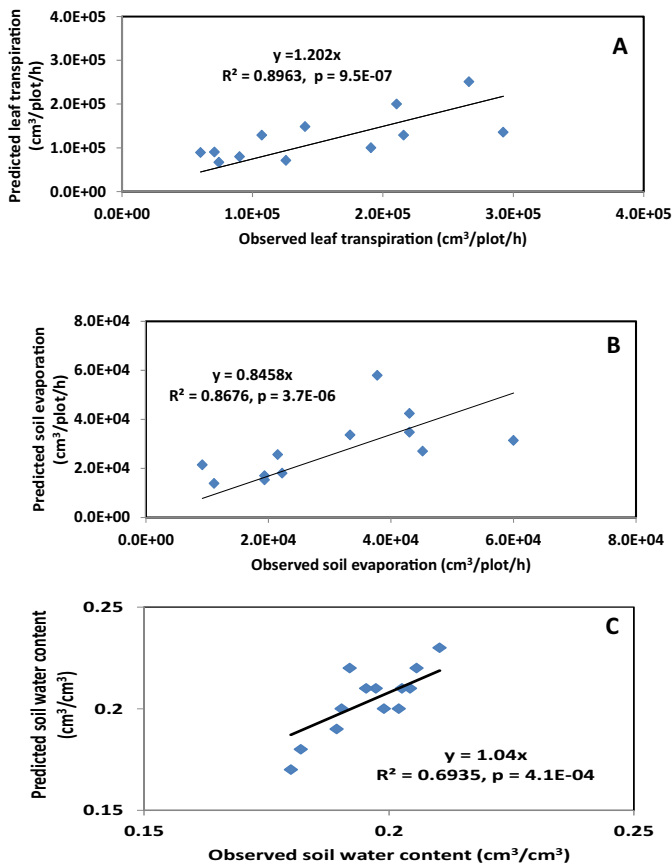


Fig. 5. Comparison of model predicted and field measured leaf transpiration (A), soil evaporation (B), and soil water content (C) during model calibrations.

this scenario, all of the simulation conditions and input parameter values were the same as those used in model validation. The second scenario was selected to project the potential impacts of relatively wet and dry soil conditions upon hydrological processes and eucalyptus water dynamics with increasing and decreasing the annual rainfall rate by fourfold from the base scenario, respectively, for the wet and dry conditions. In this second scenario, all of the simulation conditions and input parameter values were the same as those used in the first scenario except for the rainfall rates and simulation period (2 years). Therefore, comparison of the simulation results from the two scenarios allowed us to evaluate the eucalypt plantation water use status under different soil water regimes. The simulation started at the first day of January and terminated at the end of December in the first year for Scenario 1 and in the second year for Scenario 2. A 3-year-old eucalypt plantation grown in a sandy soil was selected as the modeled domain (Fig. 1), which had the same size and hydrological conditions as those from our field experimental plot. The input parameter values used for these scenarios were given in Table 1.

3.1. Daily variation

Daily variations of soil evaporation, leaf water transpiration, root water uptake, and cumulative water use over a week (168 h) simulation period are shown in Fig. 7. This figure shows a typical diurnal water variation pattern, with increasing during the day followed by decreasing at night. The diurnal variations of soil water evaporation occurred because of the daily cycle of soil temperature, which normally warms during the day and cools at night. The evaporation rate from 0 (midnight) to 6 h (early morning) was near zero as a result of cool temperatures. Then, the rate increased from

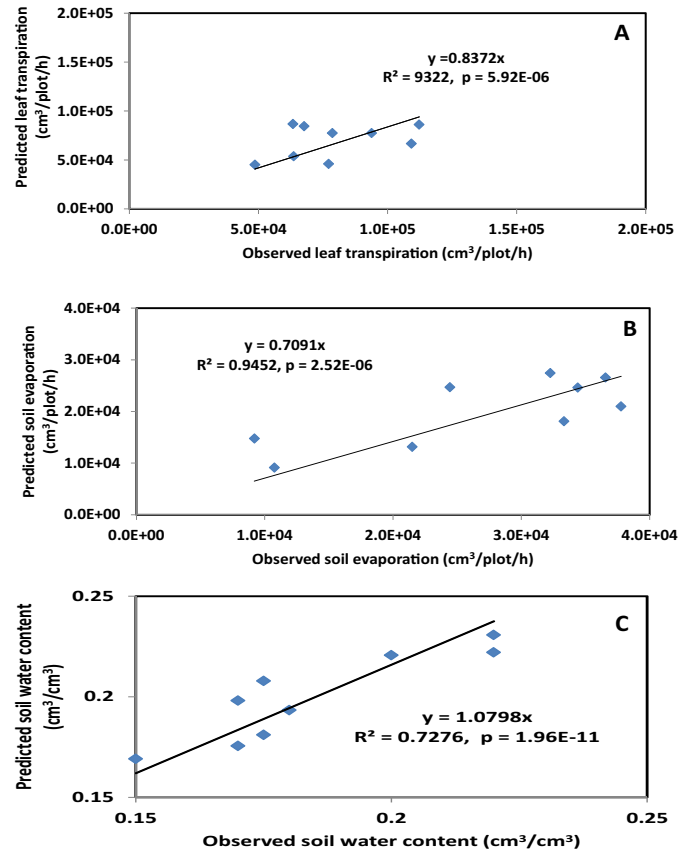


Fig. 6. Comparison of model predicted and field measured leaf transpiration (A), soil evaporation (B), and soil water content (C) during model validations.

6 h (sunrise) and reached its maximum at $2.3E+04$ cm³/h/plot at 13 h (Fig. 7A) and finally decreased from 13 h to near zero at 18 h as sunset. Similar diurnal variation patterns were obtained for leaf transpiration and evapotranspiration (ET) (Fig. 7A). The rate of leaf transpiration from 0 to 6 h was close to zero as a result of leaf stomata closed at night. Then, transpiration occurred during the day because of leaf stomata opened and the transpiration rate increased from 6 to 13 h and decreased from 13 to 18 h dramatically, and finally was close to zero from 18 to 24 h. This daytime variation in transpiration rate was similar to that of daytime normal air temperature cycle since air temperature is one of the factors controlled leaf water transpiration. The maximum rate of leaf transpiration at 13 h was $1.2E+05$ cm³/h/plot, which was about five times greater than that of soil evaporation at the same time period. This value is within the range reported by Lane et al. (2004). These authors reported that the rate of transpiration was about 3–6 times greater than that of soil evaporation. The rate of ET shown in Fig. 7A was the sum of evaporation and transpiration and its maximum value was $1.43E+05$ cm³/h/plot.

Starting from the first daily cycle, the maximum diurnal rates of evaporation, transpiration, and ET increased gradually during a one-week simulation period (Fig. 7A). This occurred because these rates are the seasonal phenomena and are controlled primarily by temperatures and eucalypt growth characteristics, which increase from winter to summer and decrease from summer to the following winter (Fig. 2). Eqs. (4) and (6) used to calculate soil evaporation and eucalyptus transpiration were formulated based on our annual experimental data, which reflected these variations.

Analogous to the case of soil evaporation and leaf transpiration, changes in the rate of root water uptake showed a typical diurnal behavior: an increase during the day followed by a decrease at night

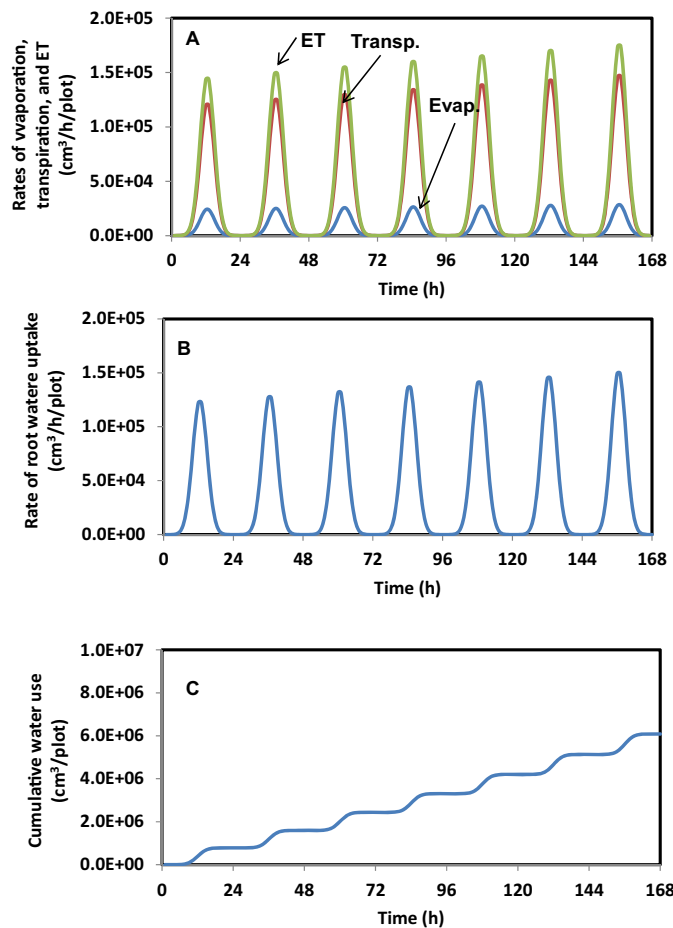


Fig. 7. Predicted diurnal rates of ET (A) and root water uptake (B) as well as predicted cumulative water use by eucalyptus (C) during a week simulation in January.

(Fig. 7B). This occurred because the rate of root water uptake in the soil is primarily controlled by the rate of leaf water transpiration (Nobel, 1983). Our field experiment showed that on average about 98% of water taken up by roots is used for leaf water transpiration (Eq. (7)) and the rest of 2% is used for eucalyptus growth. Therefore, the rate of root water uptake is slightly higher than that of leaf water transpiration.

Fig. 7C showed the cumulative water use by the eucalypt plantation during a one week simulation. This figure was constructed by summing the hourly root water uptake in volume per plot. The cumulative eucalyptus water use increased with simulation time and was $6.1\text{E}+06 \text{ cm}^3/\text{plot}$ per week. This finding was very similar to the one reported by Morris et al. (2004). These authors found that the water use by eucalyptus was $6.7\text{E}+06 \text{ cm}^3/\text{plot}$ per week during the same time period in January.

3.2. Monthly variation

Monthly variations of rainfall, soil water content, and percolation over a one-year simulation period are shown in Fig. 8. The rainfall data were measured from the experimental plot and were presented here for references, while the other data in the figure were the simulation results. From January to March, the soil water content was primarily influenced by the rainfall events (Fig. 8A and B). That is, the soil water content increased when the rainfall took place. However, this was not true in April because the soil water content decreased when the rainfall occurred (Fig. 8A). This could happen because the soil water content depends not only on rainfall but also on ET. The rate of ET was higher in April than in January

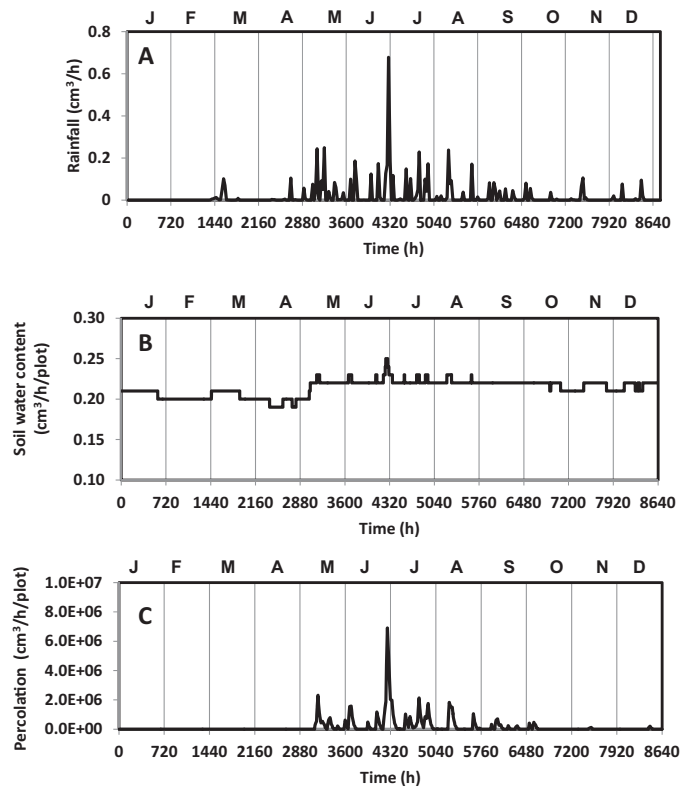


Fig. 8. Monthly variations of measured rainfall (A), predicted soil water content (B), and predicted percolation (C).

(Fig. 4). When the rate of rainfall was lower than the rate of ET, the soil water content could decrease. From May and September, the soil water content increased because of the high rainfall rate and long duration during this wet season. It is, therefore, apparent that soil water content in the eucalyptus plantation was controlled by the rates of ET and rainfall as well as the rainfall duration.

Soil water percolation was primarily observed during the wet season from May to September for the one-year simulation (Fig. 8C). The magnitude and duration of the percolation corresponded well with those of rainfall events. The maximum percolation rate of $6.9\text{E}+06 \text{ cm}^3/\text{h}/\text{plot}$ was observed in late June (Fig. 8C) when the maximum rainfall rate was $0.68 \text{ cm}^3/\text{h}$ (Fig. 8A). Soil percolation occurred when the soil water content was greater than its field capacity and was highly driven by rainfall. Fig. 8C further revealed that no percolation occurred from January to April because the soil water content (Fig. 8B) had never exceeded its field capacity ($0.22 \text{ cm}^3/\text{cm}^3$) during this period. Furthermore, no surface ponding and runoff occurred because this sandy soil had never been saturated ($0.38 \text{ cm}^3/\text{cm}^3$) for the simulation conditions used in this study.

Fig. 9 shows the rates of evaporation, transpiration, and root uptake over a one-year simulation period from the soil and eucalyptus. These rates had the monthly variation patterns. In general, the rate of evaporation was lowest in January and highest in August, which corresponded well with the monthly temperature variations in the Leizhou Peninsula where the experiment was conducted. However, the highest rates of leaf water transpiration and root water uptake were observed in early July, which was about one month earlier than that of the soil evaporation. We attributed this time discrepancy to the seasonal growth characteristics of the eucalyptus. Although the rate of soil water evaporation is governed by soil temperature and water content, the rate of leaf water transpiration is controlled not only by soil

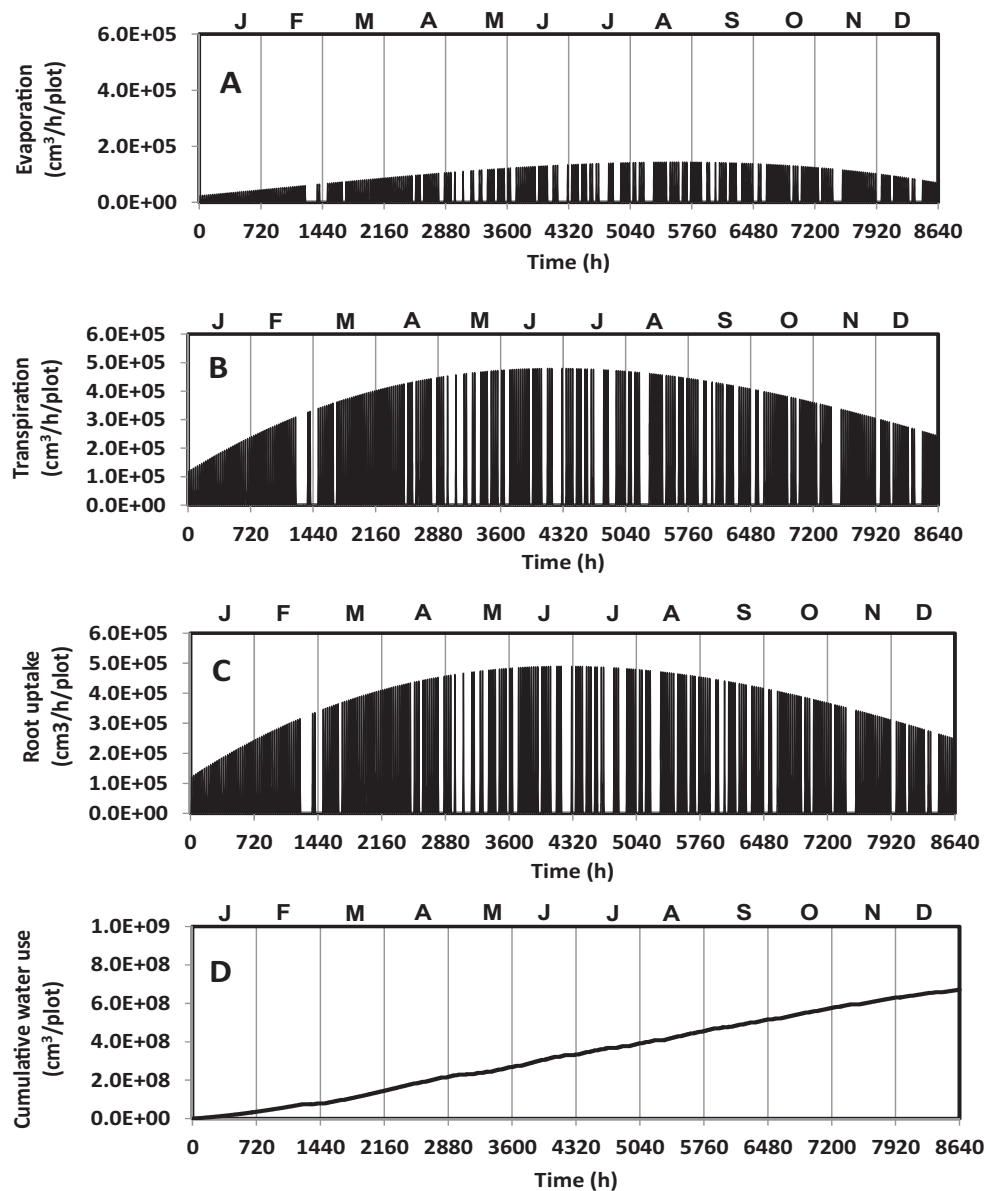


Fig. 9. Predicted monthly rates of evaporation (A), transpiration (B), and root uptake (C) as well as predicted cumulative water use (D) by eucalyptus.

temperature and water content but also by other factors such as the seasonal growth characteristics.

Fig. 9 also reveals that the rates of evaporation, transpiration, and root uptake were highly related to the rainfall intensity and duration. In this modeling study, we assumed no soil evaporation and leaf transpiration occur during rainy days (Hillel, 1982; Nobel, 1983). A comparison of the rates among evaporation, transpiration, and root uptake showed that these rates were in the following order: root uptake > transpiration > evaporation. Overall, these rates were highest during summer and lowest in winter. Furthermore, a linear increase in cumulative water use by the eucalyptus was observed during the one-year simulation (Fig. 9D) and the cumulative water use was $6.9 \times 10^8 \text{ cm}^3/\text{plot}$ at the end of the year. This finding was within the range reported by Morris et al. (2004). These authors observed that the water use by eucalyptus is $8.7 \times 10^8 \text{ cm}^3/\text{plot}$ per year at the same experimental location used in this study. Since the number of trees was 213 for the entire experimental plot, the cumulative water use was therefore $3.2 \times 10^6 \text{ cm}^3/\text{tree}$.

3.3. Wet and dry conditions

Monthly impacts of the wet and dry soil conditions on eucalyptus ET and water use over a two-year simulation period are shown in Fig. 10. The wet soil condition was accomplished with increasing the rate of rainfall from the base scenario by 4-fold, whereas the dry soil condition was achieved with decreasing the rate of rainfall from the base scenario by 4-fold. Fig. 10A shows that the rates of ET among the base, wet, and dry soil conditions were about the same for the first year's simulation period except for the dry condition in December when the soil water content was $0.17 \text{ cm}^3/\text{cm}^3$ (Fig. 10B). This was so because the soil evaporation was trivial at this water content in a sandy soil (Hillel, 1982). Large discrepancy in the rate of ET between the base (or wet) soil condition and the dry soil condition started to develop from January to June during the second year's simulation period. For example, the rate of ET was $7.9 \times 10^7 \text{ cm}^3/\text{plot}$ for the base (or wet) soil condition in March but was $5.0 \times 10^7 \text{ cm}^3/\text{plot}$ for the dry condition in the same month. The former was about 3.6-fold greater than the latter. This occurred

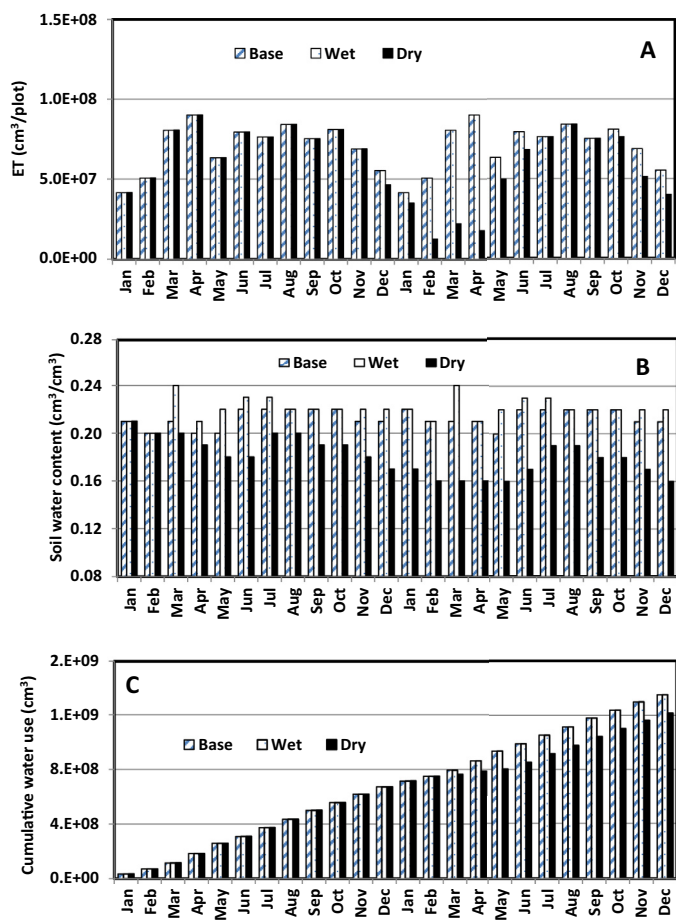


Fig. 10. Comparisons of ET, soil water content, and cumulative water use among the normal (base), wet, and dry soil conditions for a two-year simulation period.

because the soil water content was $0.16 \text{ cm}^3/\text{cm}^3$ (wilting point) in this month (Fig. 10B). Under this low water content, soil evaporation, root water uptake, and leaf water transpiration were near zero. It should be noted no difference in the rate of ET was observed between the base and wet soil conditions. Therefore, the impact of soil water content on ET in a eucalypt plantation occurred when the soil water content was below $0.17 \text{ cm}^3/\text{cm}^3$.

Comparison of cumulative water use by eucalyptus among the base, wet, and dry soil conditions is shown in Fig. 10C. Analogous to the case of ET, little to no difference in cumulative water use by eucalyptus was observed among the three soil conditions for the first year's simulation period as the soil water content was not a limiting factor during this simulation period. Difference started to develop for the second year's simulation when the soil water content was below $0.17 \text{ cm}^3/\text{cm}^3$. The cumulative water use was $1.35 \text{E} + 09 \text{ cm}^3/\text{plot}$ for the base and wet soil conditions at the end of the 2-year simulation period but $1.21 \text{E} + 09 \text{ cm}^3/\text{plot}$ for the dry condition at the same simulation period. The latter was 1.1-fold lower than the former, resulting from the low soil water content.

4. Summary

In this study, a model for hydrological processes and water consumption in a eucalypt plantation was developed using the STELLA software. The model was calibrated with a good agreement between the model predictions and the field measurements obtained from our experiment. Two simulation scenarios were performed in this study. The first scenario (base scenario) was chosen to quantify soil hydrological processes and eucalyptus water

consumption under a normal (base) climate condition for a simulation period of one year. The second scenario was selected to project the potential impacts of wet and dry soil conditions upon eucalyptus water consumption.

A typical diurnal variation pattern was observed for soil water evaporation, leaf water transpiration, and root water uptake, with increasing from sunrise to early afternoon followed by decreasing from early afternoon to sunset. A characteristic monthly variation pattern also was found for soil water evaporation, leaf water transpiration, and root water uptake, with increasing from winter to summer and decreasing from summer to the following winter.

Comparison of the rates among soil water evaporation, leaf water transpiration, ET, and root water uptake showed that these rates were in the following order: $\text{ET} > \text{root uptake} > \text{leaf transpiration} > \text{soil evaporation}$. Overall, these rates were highest during summer and lowest in winter. Our simulation further revealed that the maximum rate of leaf transpiration was about five times greater than that of soil evaporation in the eucalypt plantation, which was very close to the field measurement reported in the literature. Soil water percolation was primarily observed during the wet season and its magnitude and duration corresponded well with the rate and duration of rainfall. No surface ponding and runoff occurred for the base scenario because the sandy soil used in this study had never been saturated.

In general, the rate of evaporation was lowest in January and highest in August, which corresponded well with the local monthly temperature variations. However, the highest rates of leaf water transpiration and root water uptake were observed in early July, which was about one month earlier than that of the soil evaporation. We attributed this time discrepancy to the seasonal growth characteristics of the eucalyptus. Although no difference in ET rate was observed between the base and wet soil conditions, large discrepancy in ET rate between the wet and dry conditions started to develop when the soil water content was below $0.17 \text{ cm}^3/\text{cm}^3$ for the sandy soil used in this study.

A linear increase in cumulative water use by the eucalyptus was observed during the one-year simulation and the cumulative water use was $6.9 \text{E} + 08 \text{ cm}^3/\text{plot}$ at the end of the year. This finding was within the range reported in the literature. Analogous to the case of ET, little to no difference in cumulative water use by eucalyptus was observed among the base, wet, and dry soil conditions for the first year's simulation period as the soil water content was not a limiting factor during this simulation period. Difference started to develop for the second year's simulation when the soil water content was below $0.17 \text{ cm}^3/\text{cm}^3$. The STELLA model developed in this study was a useful tool for estimating soil hydrological processes and water use in a mature eucalypt plantation. Further study is warranted to add a model component for estimating water dynamics and biomass production in a growing eucalypt plantation.

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