Ecological Engineering 86 (2016) 290–299

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

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

Ying Ouyang[a,*], Daping Xu[b], Theodor D. Leininger[c], Ningnan Zhang[b]

[a] USDA Forest Service, Center for Bottomland Hardwoods Research, 100 Stone Blvd., Thompson Hall, Room 309, Starkville, MS 39762, United States
[b] Research Institute of Tropical Forestry, Chinese Academy of Forestry, Guangzhou 510520, China
[c] USDA Forest Service, Center for Bottomland Hardwoods Research, 432 Stoneville Road, Stoneville, MS 38776, United States

ARTICLE INFO

Article history:
Received 3 December 2014
Received in revised form 9 October 2015
Accepted 10 November 2015

Keywords:
Eucalyptus
Hydrological processes
STELLA
System dynamic model
Water use

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 cm^3/cm^3. 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.

Published by Elsevier B.V.

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

* Corresponding author. Tel.: +1 662 325 8654.
E-mail address: youyang@fs.fed.us (Y. Ouyang).

http://dx.doi.org/10.1016/j.ecoleng.2015.11.008
0925-8574/Published by Elsevier B.V.

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; Callaham 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 m^2 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 (cm^3/h), P is the rainfall rate (cm^3/h) and S, the watershed retention parameter, is estimated by

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