Water Air Soil Pollut (2013) 224:1392
DOI 10.1007/s11270-012-1392-1

A STELLA Model to Estimate Soil CO_2 Emissions from a Short-Rotation Woody Crop

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Received: 10 June 2012 / Accepted: 8 November 2012 / Published online: 24 November 2012

Abstract The potential for climatic factors as well as soil–plant–climate interactions to change as a result of rising levels of atmospheric CO_2 concentration is an issue of increasing international environmental concern. Agricultural and forest practices and managements may be important contributors to mitigating elevated atmospheric CO_2 concentrations. A computer model was developed using the Structural Thinking and Experiential Learning Laboratory with Animation (STELLA) software for soil CO_2 emissions from a short-rotation woody crop as affected by soil water and temperature regimes, root and microbial respiration, and surficial processes such as rainfall, irrigation, and evapotranspiration. The resulting model was validated with good agreement between the model predictions and the experimental measurements prior to its applications. Two scenarios were then chosen to estimate both diurnal and annual soil CO_2 emissions from a 1-ha mature cottonwood plantation as affected by soil temperature, soil (i.e., root and microbial) respiration, and irrigation. The simulation resulted in typical diurnal soil respiration and CO_2 emission patterns, with increases from morning to early afternoon and decreases from early afternoon to midnight. This pattern was driven by diurnal soil temperature variations, indicating that soil temperature was the main influence on soil respiration and CO_2 efflux into the atmosphere. Our simulations further revealed that the average seasonal soil respiration rate in summer was 1.6 times larger than in winter, whereas the average seasonal CO_2 emission rate in summer was 1.77 times larger than in winter. Characteristic annual variation patterns for soil respiration and CO_2 emission also were modeled, with both increasing from January 1 through June 30 followed by steady declines from September 1 through December 31. These results suggest that the STELLA model developed is a useful tool for estimating soil CO_2 emission from a short-rotation woody crop plantation.

Keywords CO_2 emission · Short-rotation woody crop · Soil temperature · STELLA model

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1 Introduction

The potential for changes in climatic variables, induced by emissions of greenhouse gasses from human activities and natural phenomena, is an issue of increasing international environmental concern. Since the Industrial Revolution, human activities (e.g., fossil fuel use and deforestation) have increased atmospheric carbon dioxide (CO_2) concentration. It has been reported that atmospheric CO_2 has risen from 315 ppm in 1958 to about 380 ppm at present and is projected to double in the next century (Keeling et al. 1989; Prior et al. 1994; Khalil and Shearer 2006; IPCC 2012). These gasses have strong infrared absorption capacity and trap a portion of the thermal radiation emanating from the earth's surface, potentially causing elevated atmospheric and oceanic temperatures. Under a scenario of rising global temperature, the level of the sea is likely to rise and affect the climate in most regions of the world. Changing regional climates are likely to alter forests, crop yields, and water supplies. Regional climate alterations could also affect human health, animals, and fish, and many types of ecosystems. Mechanisms to reduce the dependence of humans on fossil fuels are being developed to reduce greenhouse gaseous emissions and effects on the global climate system.

Biomass ranked the fourth largest source of energy globally (Wu et al. 2010). It can also provide a wide range of energy needs including heating, transportation fuel, and electricity generation (Caputo et al. 2005). Unlike using fossil fuels, biomass production most likely can provide benefits to the environment because no new carbon is extracted from the fossil fuel (Mago et al. 2009; Wei et al. 2009; Kim et al. 2012). Various fast-growing tree species can be grown as short-rotation woody crops to produce woody biomass as renewable and sustainable energy feedstocks for conversion into convenient solid, liquid, or gaseous fuels for industrial, commercial, and domestic uses. Currently, biomass provides about 11 % of the world's primary energy supplies. About 55 % of the 4 billion m^3 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, mainly in developing countries (IEA Bioenergy 2002).

For more than four decades, short-rotation (3–15 years to harvest) techniques have been applied to grow hardwood trees such as poplar (*Populus*), willow (*Salix*), eucalyptus (e.g., *Eucalyptus globulus*), American sycamore (*Platanus occidentalis* L.), and Eastern cottonwood (*Populus deltoides* Bartr.) as woody crops using clones exhibiting rapid growth, tolerance to pests, and suitability to site conditions for improving biomass production (Steinbeck 1999; Volk et al. 1999; Zalesny et al. 2007; Kline and Coleman 2010). Although the short-rotation techniques are a promising alternative energy source for reducing greenhouse gas emissions from energy consumption, few efforts have been devoted to estimating CO_2 emissions from the short-rotation woody crop plantation.

A variety of mathematical models have been developed to investigate ecosystem CO_2 concentrations related to global warming (Cao et al. 1992; Ouyang and Boersma 1992; Suchet and Probst 1995; Schulze et al. 1996; Moncrieff and Fang 1999; Ouyang and Zheng 2000). For example, a general global climate model (GENISIS) has been developed for simulations of changing global temperature for conditions of doubled atmospheric CO_2 (Thompson and Pollard 1995). More recently, the AR4 models are proposed to project CO_2 emissions by IPCC (2012). These models have improved our understanding of plants and ecosystems in response to rising levels of atmosphere CO_2. However, very few models have been developed to simulate soil CO_2 emissions from lands under production for short-rotation woody crops as affected by various soil water and temperature regimes. Although short-rotation woody biomass production has shown significant potential to generate adequate bioenergy supply, its impacts upon soil CO_2 emission are poorly understood. Since the production of CO_2 from the short-rotation woody crops is a complex process, it is very difficult and time consuming to quantify by experimentation alone for a variety of woody crops, for different soil and hydrological conditions, and for all possible combinations of surficial processes. Therefore, a need exists to develop a model that can help to improve current understanding and eventually predict soil CO_2 emission from lands under short-rotation woody crop production.

The objectives of this study were to: (1) develop a Structural Thinking, Experiential Learning Laboratory with Animation (STELLA) model for CO_2 emission from land under short-rotation woody crop production as affected by soil water and temperature regimes, by rates of root and microbial respirations, and by surficial processes such as rainfall, irrigation, and evapotranspiration; (2) validate the model with field experimental data from cottonwood plantation in north Florida prior to its applications; and (3) apply the model to estimate diurnal and annual CO_2 emissions from an Eastern cottonwood plantation under short-rotation woody crop production.

2 Materials and Methods

2.1 Model Development

Figure 1 is a schematic diagram showing the mechanisms of CO_2 emission from a short-rotation woody crop as affected by soil water and temperature dynamics as well as by surficial processes. The STELLA model was developed based on the mechanisms shown in this diagram. More specifically, the model was developed by coupling dynamics of water, temperature, and CO_2 in the vadose zone of the soil associated with effects of rainfall (or irrigation) and daily cycles of root and microbial respiration, evapotranspiration, and soil temperature.

2.1.1 Water Dynamics

The soil water dynamics are surface runoff, infiltration, rainfall/irrigation, root uptake, evaporation, and transpiration (Fig. 1). The surface water runoff was implemented by using Eqs. 1 and 2 (SCS 1972; Neitsch et al. 2002; Ouyang et al. 2012):

$$W_{\text{runoff}} = \frac{(\text{RI} - 0.2S)^2}{(\text{RI} + 0.8S)} \tag{1}$$

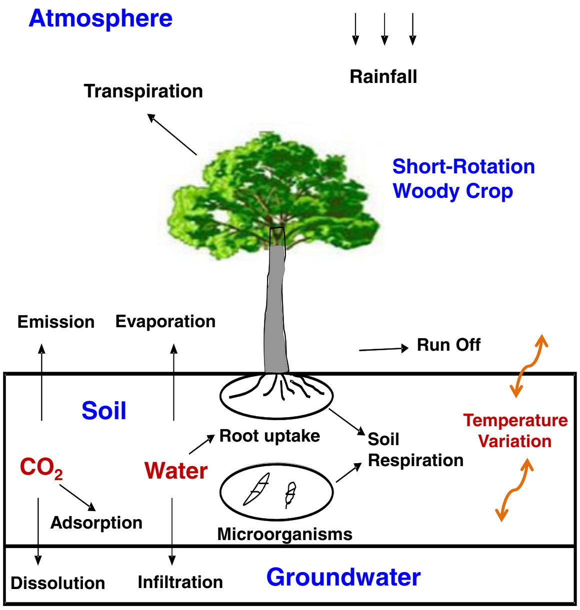

Fig. 1 A schematic diagram showing the mechanisms of CO_2 emission from a short-rotation woody crop plantation as affected by soil water and temperature regimes as well as by surficial processes

where W_{runoff} is the surface water runoff rate (in cubic meters per hour per square meter), RI is the rainfall and/or irrigation (in meters per hour per square meter), and S, the soil water retention parameter, is estimated by:

$$S = \frac{1,000}{\text{CN}} - 10 \tag{2}$$

where CN is the USDA Soil Conservation Service runoff curve number. The curve number is a function of soil type, soil drainage properties, crop type, and management practices. Soil water runoff occurs only when both the rainfall/irrigation start and the soil is saturated.

The soil water infiltration was estimated by the following equation (Mullins et al. 1993):

$$L_{\text{water}} = \alpha(\theta - f_c) \tag{3}$$

where L_{water} is the soil water vertical infiltration (in cubic meters per hour per square meter), α the drainage coefficient (per hour), θ the volumetric water content (in cubic meters per cubic meter), and f_c the field water capacity (in cubic meters per cubic meter).

The root water uptake rate in the soil is primarily controlled by leaf water transpiration. Nobel (1982) 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 loss of soil water due to root uptake is approximately equal to the loss of soil water due to leaf transpiration. The soil water evapotranspiration was estimated by the following equation:

$$\text{ET} = (E_{\text{evap}} + E_{\text{tranp}})f_d \tag{4}$$

where ET is the evapotranspiration rate (in cubic meters per hour per square meter), E_{evap} the soil surface evaporation rate (in cubic meters per hour per square meter), E_{transp} the leaf water transpiration rate (in cubic meters per hour per square meter), and f_d the diurnal factor. The diurnal changes in soil water evaporation and leaf water transpiration take place in a soil–tree system. Evaporation and transpiration commonly start at dawn when the sun rises and leaf stomata open, and stop at night when the sun sets and leaf stomata close.

2.1.2 Temperature Dynamics

Changes of CO_2, water, and temperature through the soil are interactive phenomena. Temperature changes can induce variations in water evaporation, soil respiration, and CO_2 diffusive flux. The diurnal variation of soil temperature was calculated by the following equation (Lettau 1962; Hillel 1982):

$$T(x,t) = T_a + A_o\left(\frac{\sin(\omega t - x/d)}{e^{x/d}}\right) \quad (5)$$

where T_a is the average soil temperature (in degrees Celsius), A_o the amplitude of surface temperature fluctuation (in degrees Celsius), ω the radial frequency, t the time (in hours), x the soil depth (in meters), and d the characteristic depth or damping depth (in meters). The soil temperature variations were used to calculate the soil respiration and CO_2 diffusion coefficient as described in the next section.

2.1.3 CO_2 Dynamics

Soil CO_2 dynamics include diffusive flux, root and microbial respiration, dissolution, and adsorption. The soil CO_2 emission into the near surface atmosphere was calculated as:

$$J_{CO_2} = D_{CO_2}\left(\frac{C_{CO_2}^{Soil} - C_{CO_2}^{atm}}{\Delta x}\right) \quad (6)$$

where J is the soil CO_2 flux (in milligrams per hour), C the concentration of CO_2 (in milligrams per cubic meter), D the diffusion coefficient of CO_2 (in square meters per hour), and Δx the soil depth interval (in centimeters) of interest. It should be noted that the diffusion coefficient of CO_2 is a function of soil temperature and was calculated using the equation of Partington (1949) as:

$$D_{CO_2} = \left(\frac{T}{T_r}\right)^2 D_r \quad (7)$$

where T_r is the reference soil temperature and D_r the reference CO_2 diffusion coefficient at a reference temperature.

The rate of CO_2 released by root and microbial respirations is site specific and tree species dependent. For the cottonwood species, the soil respiration equation used in this study was reported by Lee and Jose (2003) as:

$$R_{soil} = 1,266 - 0.1\text{FRP} + 12\text{MB} - 28.2\text{SOM} - 96\text{pH} \quad (8)$$

where R_{soil} is the soil (including roots and microorganisms) respiration rate (in grams C per square meter per year), FRP the fine root production (in grams per square meter per year), MB the microbial biomass (in milligrams C per kilogram dry soil), and SOM the soil organic carbon (in percent). This soil respiration rate in grams of C was then converted to the CO_2 production rate in grams of CO_2 by multiplying by a factor of 3.667 (i.e., [12+16×2]/12=3.667). It should be kept in mind that soil respiration also is a function of soil temperature. The diurnal temperature correction factor (f_T) for soil respiration was estimated based on data from Lee and Jose (2003) as:

$$f_T = 0.4493\exp(0.04T) \quad (9)$$

Therefore, the soil CO_2 production due to soil respiration in conjunction with temperature was given as:

$$R_{CO_2} = 3.667 R_{soil} A_{land} f_T \quad (10)$$

where R_{CO_2} is the soil CO_2 production rate (in grams CO_2 per year) and A_{land} the land surface area (in square meters).

The adsorption of CO_2 by soil particles and the dissolution of CO_2 into soil water were calculated by the following equations:

$$\frac{dS_{ads}}{dt} = k_{ads}\, C_{CO_2}^{soil} \quad (11)$$

$$\frac{dS_{dis}}{dt} = k_{dis}\, C_{CO_2}^{soil} \quad (12)$$

where S_{ads}/dt and S_{dis}/dt are, respectively, the rates of CO_2 adsorption to soil particles and CO_2 dissolution into soil water (in milligrams per hour), and k_{ads} and k_{dis} are, respectively, the rate constants for CO_2 adsorption and dissolution (per hour).

2.2 Model Structure in STELLA

STELLA is a modeling tool for building a dynamic modeling system by creating a pictorial diagram of a system and then assigning the appropriate values and mathematical functions to the system (Isee Systems 2006). The key features of STELLA consist of the following four tools (Fig. 2, A): (1) stocks, which are the state variables for accumulations; they collect whatever flows into and out of them; (2) flows, which are the exchange variables that control the input, output, and exchanges of information between the state variables; and (3) converters, which are the auxiliary

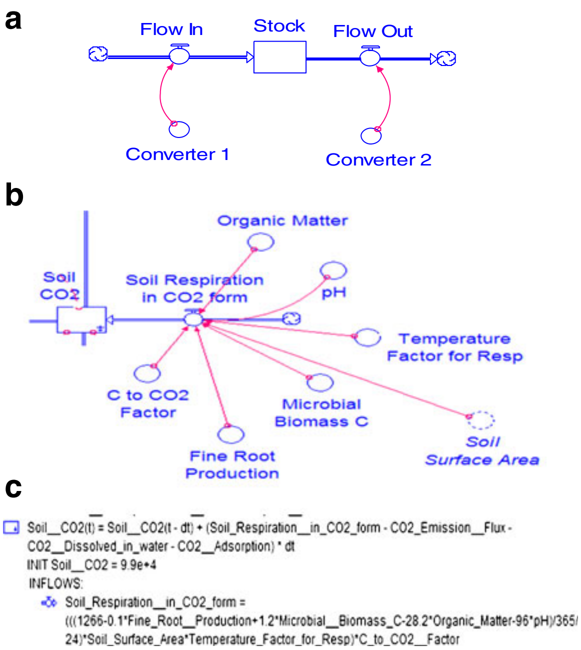

Fig. 2 A schematic diagram showing the four key features of STELLA (*A*) (1) stock, (2) flow, (3) converter, and (4) connector and the example translation of soil respiration processes into STELLA model (*B*) associated equations (*C*) that were generated automatically by STELLA

variables; these variables can be represented by constant values or by values depending on other variables, curves, or functions of various categories; and (4) connectors, which provide connections between modeling features, variables, and elements. STELLA has been widely used in the biological, ecological, and environmental sciences (Hannon and Ruth, 1994; Peterson and Richmond 1996; Costanza et al. 2002; Aassine and El Jai 2002; Ouyang 2008; Ouyang et al. 2012). A complete description of the STELLA package can be found in Isee Systems (2006).

The first step in STELLA model development is to build a basic structure to capture the processes described in the equations given above. As an example, soil CO_2 production from soil respiration described in Eqs. (8) to (10) can be translated into a STELLA model as shown in Fig. 2 (B). In this figure, the rectangle is a stock that graphically represents the mass of CO_2 stored in the soil. The flow symbol (represented by double lines with arrows and switches) represents the rate of CO_2 flow into the stock (or soil) from root and microbial respiration. The other variables are converters (represented by empty circles) that denote the rules or conditions controlling the stock and flow through the use of connectors (represented by single lines with arrows). The converters in this figure are variables for organic matter, pH, soil respiration temperature factor, soil surface area, microbial biomass C, fine root production, and a C to CO_2 conversion factor. All of these variables are defined in Eqs. (8) to (10). Once the basic structure is developed, the second step is to assign the initial values for stocks, equations for flows, and input values for converters. Then, the STELLA model equations (e.g., ordinary differential equations for this case) are automatically generated by STELLA (Fig. 2, C). Figure 3 shows a complete STELLA model for CO_2 emission from the soil of a short-rotation woody crop as affected by soil water and temperature dynamics as well as by surficial processes.

3 Results and Discussion

3.1 Model Validation

In order to apply the STELLA model for predicting CO_2 emission from the soil of a short-rotation woody crop, the model must be validated using actual field data. Model validation is a process to obtain the best fit between the observed data and simulated results without adjusting any input parameter values. In this study, we attempted to validate the model using the experimental data reported by Lee and Jose (2003). These authors studied soil respiration, fine root production, and microbial biomass in 7-year-old cottonwood and loblolly pine plantations, grown in a well-drained Red Bay sandy loam (a fine-loamy, siliceous, thermic Rhodic Paleudlt), in northwest Florida. This sandy loam soil was irrigated 2 h per day with a rate of 0.003 $m h^{-1}$. Soil respiration was measured monthly from June 2001 to May 2002 using the soda-lime technique. Fine root biomass production was quantified using the ingrowth core method during the same period. In addition, microbial biomass with chloroform fumigation–extraction procedure (Vance et al. 1987), soil temperature, soil pH, and organic matter were also measured for both species. In our modeling study, we used experimental data from the 1-h, control treatment of a cottonwood stand measured by Lee and Jose (2003). Table 1 lists all of the input parameter values used for model validation. These parameter values were obtained either from published experimental measurements or from theoretical calculations.

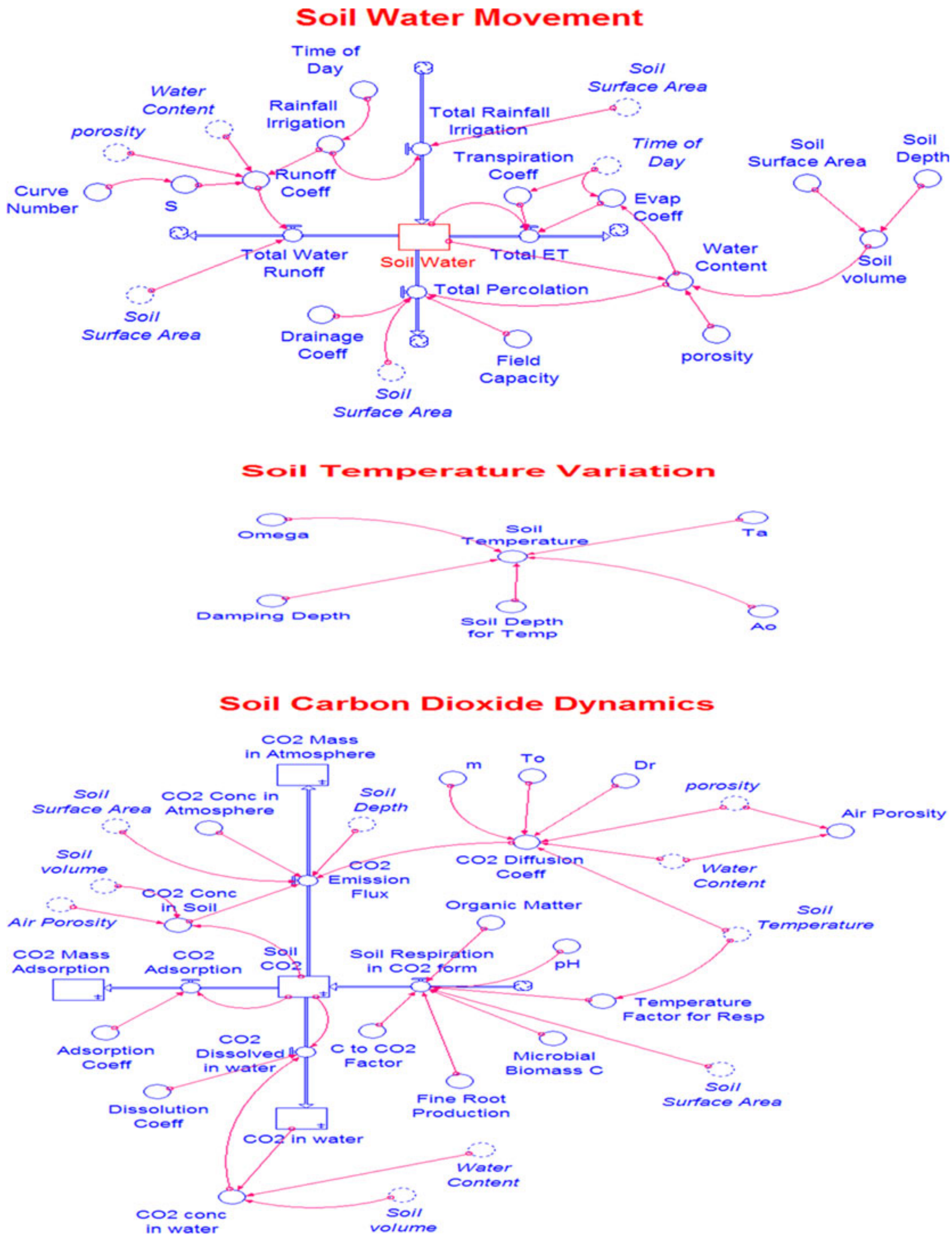

Fig. 3 A STELLA model for soil CO_2 emission as controlled by soil water and temperature regimes as well as by surficial processes

Comparisons of the measured and predicted soil respiration and soil temperature are shown in Figs. 4a and b, respectively. The regression equation of the predicted soil respiration against its corresponding measured soil respiration was $Y_{\mathrm{Prediction}}=0.9104X_{\mathrm{Measurement}}$ with $R^2=0.6205$, whereas the regression equation of the predicted soil temperature against its corresponding measured soil temperature was $Y_{\mathrm{Prediction}}=0.9004X_{\mathrm{Measurement}}$ with $R^2=0.8883$. These represent reasonably good

Table 1 Input parameter values used for model validation and applications

Soil temperature variation		
Average soil temperature as a function of time	$-8E-07t^2+0.0079t+2.422$	Lee and Jose (2003)
Amplitude of surface temperature (°C)	10	Ouyang et al., (2002)
Soil temperature damping depth (m)	0.15	Hillel (1982)
Radial frequency	$2\pi/24$	Ouyang et al. (2002)
CO_2 flux dynamic		
CO_2 in atmosphere (gm^{-3})	0.6134	Ouyang and Boersma (1992)
CO_2 diffusion coefficient (m^2/h)	0.004	Jabro et al. (2012)
Diurnal soil temperature factor	0.4493 Exp(0.04temperature)	Estimated from Lee and Jose (2003)
pH	5.7	Lee and Jose (2003)
Microbial Biomass C (mg C/kg dry soil)	144.3	Lee and Jose (2003)
Fine root production (g/m^2/year)	220.8	Lee and Jose (2003)
Soil organic matter (%)	2.4	Lee and Jose (2003)
CO_2 dissolution rate constant (1/h)	0.0045	Estimated from Shindo et al. (1995)
Conversion factor from C to CO_2	3.667	http://cdiac.ornl.gov/pns/convert.html
CO_2 adsorption rate coeff (1/h)	3.6E−6	Estimated from Molz et al. (1986)
Initials soil CO_2 mass (g)	99,370.8	Estimated based on initials soil CO_2 concentration and volume

agreements between the model predictions and the experimental measurements.

Plots of the measured and predicted soil respiration and soil temperature against the simulation time over a 1-year period are shown in Figs. 4c and d. The model predictions were graphically fitted to the experimental measurements. Since no soil water content data were provided by Lee and Jose (2003), we could not validate the model for the water dynamic component although these authors stated that the average soil volumetric water content at 12 cm depth is 15 %, which was consistent with our model predictions. These authors also found that soil water did not have a significant effect on soil respiration in their study. Similarly, no data for soil CO_2 emission into the atmosphere were provided by Lee and Jose (2003) for validating the CO_2 emission component of the model. However, based on a study in Aiken, South Carolina (Coleman, 2003), about 95 % of CO_2 production due to respiration from soils supporting cottonwood was emitted into the atmosphere, which also was consistent with our CO_2 emission predictions.

3.2 Model Application

To gain a better understanding of CO_2 emission from soils of a short-rotation woody crop as affected by surficial processes, two simulation scenarios were performed in this study. The first scenario investigated the diurnal CO_2 efflux in response to daily cycles of surficial processes. The second scenario evaluated the seasonal and annual CO_2 emissions as affected by the corresponding variations of soil respiration and soil temperature. A mature cottonwood stand with an area of 1 ha and a soil depth of 1 m was selected as the modeled domain, which was similar to the cottonwood treatment reported by Lee and Jose (2003). The conceptual diagram of the modeled domain used for these scenarios was similar to the one shown in Fig. 1. The cottonwood was irrigated at a rate of 0.003 mh^{-1} for 2 h every day. Input parameter values used for these scenarios were given in Table 1.

3.2.1 Diurnal Co_2 Emission (Scenario 1)

This scenario investigated the daily CO_2 efflux from the soil as controlled by daily cycles of soil respiration, surface evapotranspiration, and soil temperature. A 1-year simulation period was chosen for this scenario, which started at 0 h (midnight) on January 1 and stopped on December 31. The simulation results for this scenario were presented in Figs. 5 and 6 and discussed below.

Daily variations of soil temperature at a depth of 0.3 m over a 1-week (168 h) simulation period are

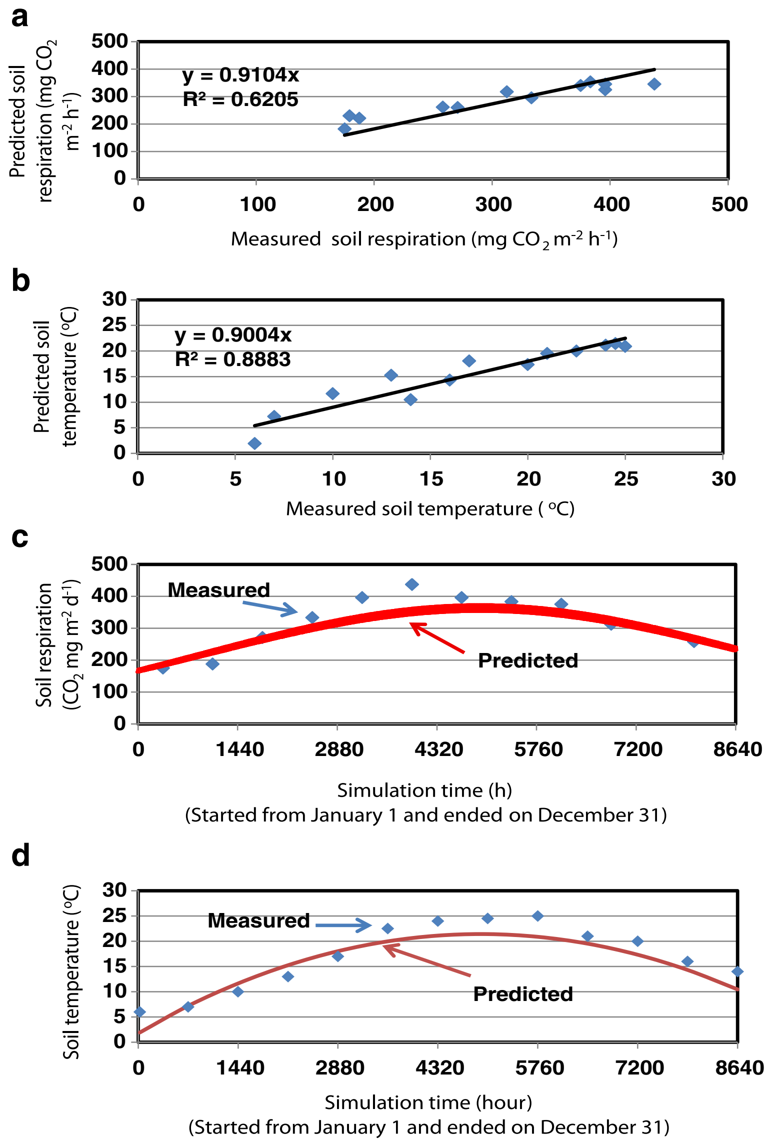

Fig. 4 Comparison of model-predicted and field-measured soil temperatures and respirations

shown in Fig. 5a. This figure showed a characteristic diurnal temperature pattern, with warming from sunrise to early afternoon followed by cooling from early afternoon to sunset. These temperature variations occurred because of the solar energy flux into or out of the soil by means of shortwave radiation, longwave radiation, and heat evaporation and condensation. Figure 5a further reveals that soil temperature increased diurnally. For example, the maximum soil temperature was 3.3 °C at 15 h (the first cycle) and was 4.3 °C at 136 h (the sixth cycle). The latter was 1° higher than the former. This was consistent with the experimental measurements (Fig. 4d) and occurred because average air temperature increased starting in January. Surface soil temperature, respiration, and CO_2 emission interact in ecosystems. As the soil temperature varies, the soil respiration and CO_2 emission change accordingly.

A similar daily variation pattern was obtained for soil respiration (Fig. 5b). The soil respiration (i.e., root and microbial respiration) increased from morning to early afternoon and decreased from early afternoon to midnight each day. This daily variation pattern was driven by diurnal soil temperature variations (Fig. 5a). Analogous to the case of soil temperature, soil respiration also increased diurnally. For instance, the maximum soil respiration was about 2.8E+04 $mgCO_2h^{-1}$

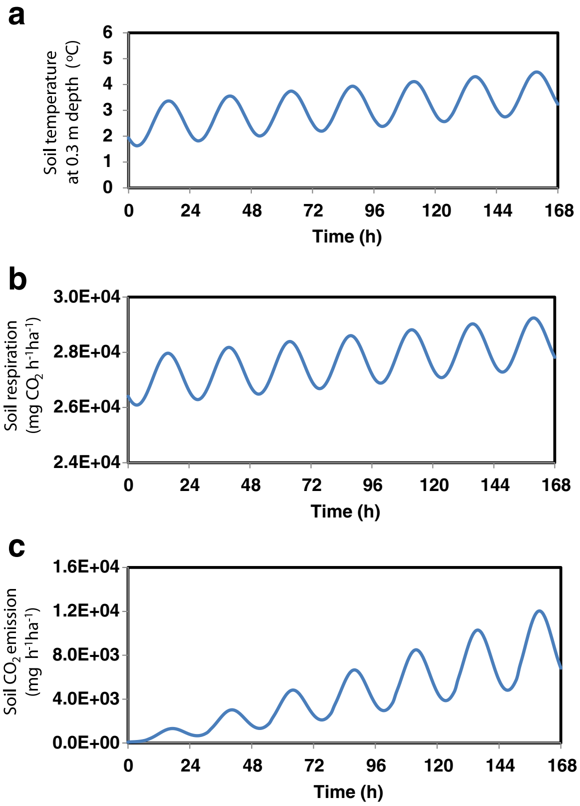

Fig. 5 Predicted daily variations of soil temperature, soil respiration, and CO_2 emission from 1 ha of cottonwood plantation

at 15 h (the first cycle) and was about 2.9E+04 mg $CO_2 h^{-1}$ at 136 h (the sixth cycle). The latter was about 3.5 % greater than the former, which occurred because the soil temperature increased.

Starting from the first day, the rate of soil CO_2 efflux into the atmosphere increased consecutively during a 1-week simulation period (Fig. 5c). This rate was calculated using Eq. (6) for the 1-ha simulation area. The initial soil CO_2 concentration was assumed to be the same as that in the atmosphere (Table 1). The variation pattern of CO_2 efflux was more or less similar to that of soil temperature and respiration (i.e., increasing during the day and decreasing during the night), but with a sequential increase in magnitude. The daily variations of CO_2 efflux were driven by soil temperature and respiration, whereas the increase in the CO_2 efflux rate was due to the increase in soil CO_2 concentration as a result of soil respiration. The maximum rate of CO_2 efflux was 1219 mgh^{-1} for the first daily cycle at 15 h and was 10,285 mgh^{-1} for the sixth daily cycle at 136 h. The maximum rate between these two daily cycles differed by a factor of about 8.4. We attributed this difference to the increase in soil CO_2 concentration produced from the soil respiration.

Daily variations of surface irrigation, evapotranspiration, and volumetric water content for a 1-week simulation are shown in Fig. 6. The rate of surface irrigation (Fig. 6a) was 0.003 mh^{-1} with the irrigation duration of 2 h per day, which was reported by Lee and Jose (2003). The rate of evapotranspiration showed a typical daily behavior, with increases during the day and decreases at night, which was a result of daily cycles of soil temperature and leaf water transpiration. Evaporation and transpiration commonly start at dawn when the sun rises and leaf stomata open, and stop at night when the sun sets and leaf stomata close. Based on the simulation conditions used in this scenario, the soil water content was basically constant over the entire simulation period (Fig. 6c). The effect of soil water content on soil CO_2 emission under these simulation conditions was not significant as confirmed by Lee and Jose. However, it should be noted that under natural conditions (without human control), soil water content could play an important role by affecting the soil oxygen concentration needed for soil respiration and by affecting the volume of air space in soil for CO_2 diffusive flux.

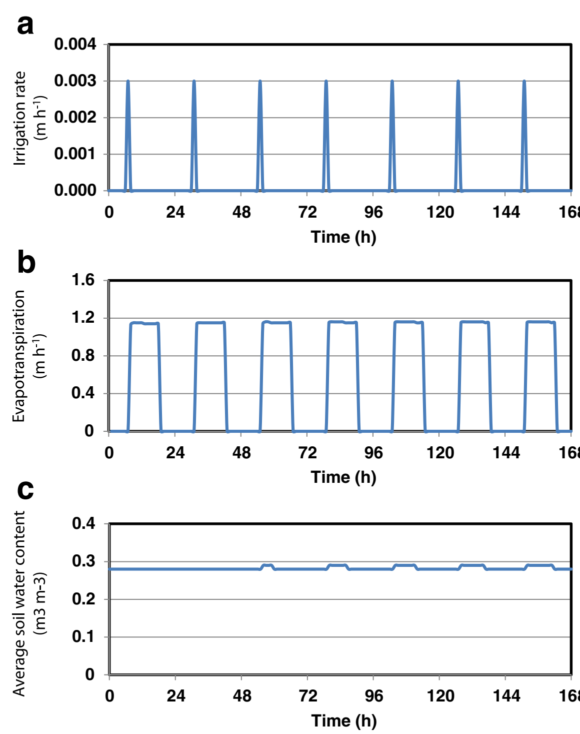

Fig. 6 Daily variations in predictions of surface irrigation, evapotranspiration, and soil water content in 1 ha of cottonwood plantation

3.2.2 Seasonal and Annual CO_2 Emission (Scenario 2)

This scenario evaluated the seasonal and annual CO_2 emission as affected by seasonal and annual changes in soil temperature and respiration. All of the input parameter values were the same as those for the first scenario except for simulation period, which was set for 10 years. Simulation results for this scenario are presented in Figs. 7 and 8.

Average seasonal variations of soil temperature at the 0.3-m depth over a 10-year simulation period are shown in Fig. 7a. This figure showed that soil temperature was highest in summer and lowest in winter as we expected. There was about a 10 °C difference between the two extremes. A similar seasonal variation pattern was obtained for soil respiration. The average rates of seasonal soil respiration were in the following order: summer>fall >spring>winter (Fig. 7b). The average rate in summer was 1.6 times greater than in winter, primarily due to the increase in soil temperature during summer.

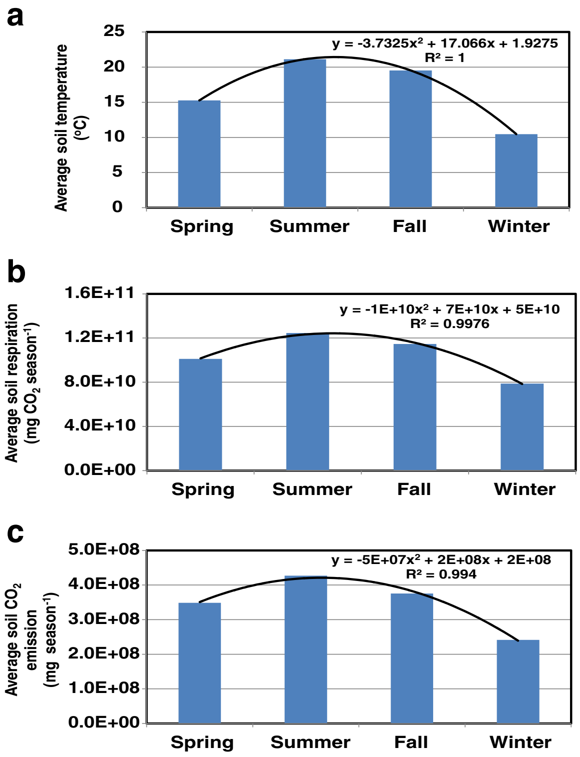

Fig. 7 Predicted seasonal variations of soil temperature, soil respiration, and CO_2 emission from 1 ha of cottonwood plantation

Figure 7c shows the average rate of seasonal soil CO_2 emission from soil supporting cottonwood. This rate had a similar seasonal variation pattern to that of soil respiration. That is, the rate increased from spring to summer and decreased from summer to winter. The average rate was 4.27E+08 mg season^{-1} in summer and was 2.41E+08 mg season^{-1} in winter. Soil CO_2 emission was about 1.77 times larger in summer than in winter.

Annual changes in soil temperature at a depth of 0.3 m over a 10-year simulation period are shown in Fig. 8a. This figure showed a typical annual temperature pattern, with warming from winter to summer followed by cooling from summer to winter. This temperature variation pattern occurred due to the annual solar radiation variation. Similar annual variation patterns were obtained for soil respiration and CO_2 emission (Figs.8b and c). These annual variation patterns were driven by the annual soil temperature variation.

The mass balance of soil CO_2 in the cottonwood plantation at the end of the 10-year simulation period was estimated using the following equation: mass balance (in percent)=soil CO_2 depletion/(soil CO_2 production + soil CO_2 storage). The soil CO_2 depletion included

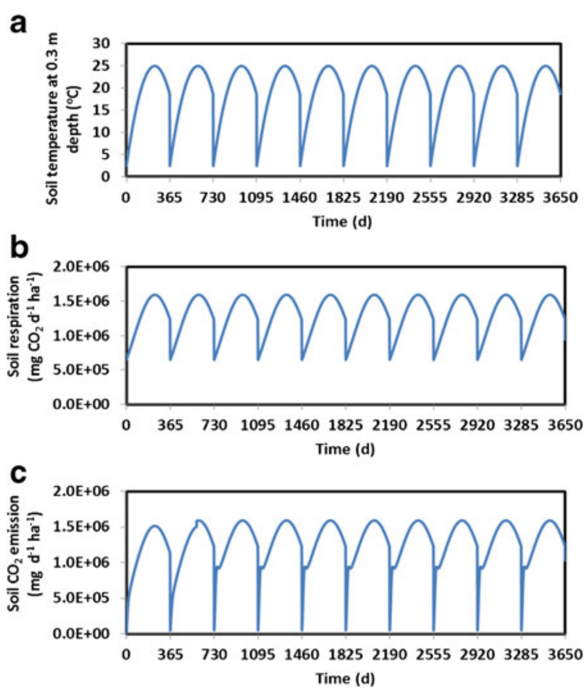

Fig. 8 Predicted annual variations of soil temperature, soil respiration, and CO_2 emission from 1 ha of cottonwood plantation

emission, dissolution, and adsorption, whereas the soil CO_2 production was from root and microbial respirations. With a mass balance of 0.04 %, we concluded that the model successfully predicted the soil CO_2 budget for the cottonwood plantation.

4 Summary

In this study, a model for soil CO_2 emission from soil supporting a short-rotation woody crop as affected by soil water and temperature regimes, soil respiration, and surficial processes was developed using the commercial available STELLA software. The model was validated with good agreement between the model predictions and values measured in field experiments documented in the literature. Two scenarios were then chosen to estimate the diurnal and annual soil CO_2 emissions from a cottonwood plantation.

A typical diurnal variation pattern was observed for soil temperature, respiration, and CO_2 emission, with increases from sunrise to early afternoon followed by decreases from early afternoon to sunset. A characteristic seasonal and annual variation pattern also was found for soil temperature, respiration, and CO_2 emission, with increases from spring to summer and decreases from summer to winter. In general, soil respiration and CO_2 emission from the cottonwood plantation were strongly controlled by soil temperature. As the soil temperature varied, so did the soil respiration and CO_2 emission.

The rate of evapotranspiration showed a typical daily pattern, with increases during the day and decreases at night, which was a result of daily cycles of soil temperature and leaf water transpiration. The effect of soil water content on soil CO_2 emission for the simulation conditions used in this study was not significant. However, it should be noted that under natural conditions, soil water content could affect soil oxygen concentration needed for soil respiration and soil air spaces needed for CO_2 diffusive flux.

The STELLA model developed in this study was shown to be a useful tool for estimating soil CO_2 emission from soil supporting a short-rotation woody crop. However, the model was developed to estimate CO_2 emission from soil with a mature short-rotation woody crop and not with a developing short-rotation woody crop. The rates of CO_2 production by photorespiration and CO_2 consumption by photosynthesis were not included in the model. Therefore, further study is warranted to estimate the overall CO_2 budget in a soil–tree–atmosphere continuum.

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