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A graphical user interface for numerical modeling of acclimation responses of vegetation to climate change ☆

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ABSTRACT

Ecophysiological models that vertically resolve vegetation canopy states are becoming a powerful tool for studying the exchange of mass, energy, and momentum between the land surface and the atmosphere. A mechanistic multilayer canopy–soil–root system model (MLCan) developed by Drewry et al. (2010a) has been used to capture the emergent vegetation responses to elevated atmospheric CO_2 for both C_3 and C_4 plants under various climate conditions. However, processing input data and setting up such a model can be time-consuming and error-prone. In this paper, a graphical user interface that has been developed for MLCan is presented. The design of this interface aims to provide visualization capabilities and interactive support for processing input meteorological forcing data and vegetation parameter values to facilitate the use of this model. In addition, the interface also provides graphical tools for analyzing the forcing data and simulated numerical results. The model and its interface are both written in the MATLAB programming language. Finally, an application of this model package for capturing the ecohydrological responses of three bioenergy crops (maize, miscanthus, and switchgrass) to local environmental drivers at two different sites in the Midwestern United States is presented.

1. Introduction

The acclimation responses of vegetation to climate change remains a challenging problem for exploring land–atmosphere interactions (Sellers et al., 1997; Baldocchi et al., 2002; Drewry et al., 2010a). Capturing these responses to elevated concentrations of atmospheric carbon dioxide (CO_2) and temperature variability is critical to predicting the potential impacts of climate change on hydrology and ecosystem functions (Ewert, 2004; Drewry et al., 2010b; Le et al., 2011). Numerical modeling has evolved to incorporate essential interactions of the structural, ecophysiological and biochemical functioning of the canopy and the root systems that can realistically simulate such processes (Drewry et al., 2010a; Vos et al., 2010). These advanced models require the resolution of vertical radiation and thermal regimes within the canopy and the tight coupling between the leaf ecophysiology, energy balance and soil moisture state (Drewry et al., 2010a, 2010b).

A 1-D multilayer canopy–soil–root system model (MLCan) was developed by Drewry et al. (2010a) to describe the synthesis of coupled canopy, leaf, root and soil processes resolved vertically through the canopy and soil domains. This point column vertical model has been validated for vegetation canopies that utilize the two most common photosynthetic pathways, C_3 (Drewry et al., 2010a) and C_4 (Drewry et al., 2010a; Le et al., 2011) and their combinations (Quijano et al., 2012), providing a platform that can be used to evaluate the role of photosynthesis on ecosystem processes across a wide range of climate regimes. It has also been validated for both ambient and elevated CO_2 conditions (Drewry et al., 2010a, 2010b; Le et al., 2011), making it a useful tool to study the emergent responses of vegetation to environment in present and future climates. As with many complex numerical models, parameter specification and the organization and input of forcing data often require specifying numerical values and file names as hard-coded values at various locations in the code. This process can lead to errors for less experienced users, potentially deterring broad adoption of a model. Here we present a graphical user interface (GUI) designed to abstract the specification of input data and parameter values into a more user-friendly framework that facilitates the visualization of input time series and a variety of simulation outputs.

☆ Code availability: The source code for the GUI and the MLCan model have been released for research and education purposes, and are available for download at https://github.com/HydroComplexity/MLCan. A user manual showing step by step tutorials and example is also uploaded on the website for new users. The GUI can be run under Windows, Mac, and Linux operating systems.

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The objective of this study is twofold. First, we present a GUI designed to facilitate the use of MLCan, making it more accessible for a broader range of interested users. The organization and important features of the GUI, as well as the basic steps needed to specify parameter values, input forcing data, and for running the model are discussed. Second, this paper closes with the presentation of case studies that demonstrate the use of MLCan using this GUI to the study of the ecohydrological responses of three bioenergy crops (maize, miscanthus, and switchgrass) to local environmental drivers at two different sites in the Midwestern United States.

2. A GUI for multilayer canopy–soil–root model

Both the MLCan model and the GUI presented here have been developed in the MATLAB programming language (Mathworks, Natick, MA, USA). MATLAB is largely platform-independent, being available for many operating systems (e.g. Linux, Windows, Mac OSX). The MLCan model aims to resolves the canopy radiation and meteorological microenvironment and leaf-level ecophysiological states at multiple canopy levels to determine canopy atmosphere scalar fluxes (CO_2, latent and sensible heat) (see Fig. 1). The formulation of MLCan was presented by Drewry et al. (2010a). We refer interested users to that paper for information on the design, formulation and characteristics of MLCan. The GUI presented here is organized around a set of windows each corresponding to a step in the process of initializing and running MLCan, with the aim being to reduce errors in model setup and data processing through a more intuitive framework.

The main window of the GUI is divided into the five tasks depicted on the left side of Fig. 2. Each task in the main window represents one of the unique requirements for specifying and running MLCan and examining simulation output. New users are guided through the use of the main menu by way of concise instructions displayed on the right side of the main menu. Important features of each component in the GUI are discussed below.

2.1. Model setup

The *Model Setup* provides the functionality for specifying the geographic location and elevation of the site, as well as the structural characteristics of the vegetation canopy, root and soil systems (Fig. 3). Geographic location and elevation are required for azimuth and zenith angle calculations that allow accurate estimation of the canopy radiation regime (Campbell and Norman, 1998). The vegetation canopy is decomposed into multiple layers, allowing for resolution of canopy environmental variables (i.e. wind speed, temperature, humidity, radiation fluxes) that can significantly impact the fluxes of CO_2 and energy from the foliage distributed throughout the canopy. This requires the specification of the vertical distribution of the Leaf Area Density (LAD). The number of canopy layers, as well as the density of foliage at each layer, is user-defined. Finer resolution with more layers is better for model accuracy (Drewry et al., 2010a) but requires more time for computation. Therefore the choice of canopy resolution should balance these important criteria. Users are allowed to input the LAD profile via the table built into the GUI, or by importing data files. The supported

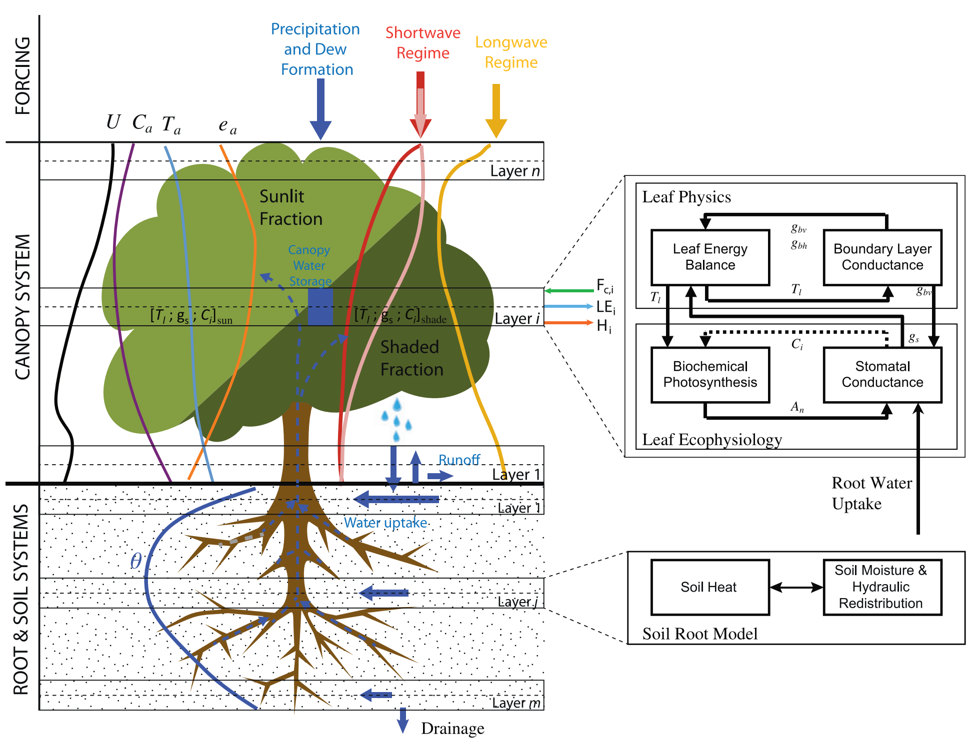

Fig. 1. Schematic of the canopy, root, and soil system (MLCan) model. Shortwave radiation components (photosynthetically active and near-infrared radiation) are attenuated through the canopy, accounting for absorbed, transmitted, and reflected fractions at each layer. Direct (red) and diffuse (pink) components of the shortwave streams are considered separately to account for sunlit and shaded leaf fractions at each canopy level. The longwave radiation regime accounts for absorption and emission by the foliage in each canopy layer. Transmitted radiation fluxes drive the soil temperature model. Wind speed is resolved within the canopy space, as are gradients in concentrations of CO_2, water vapor, and heat. Rainfall and dew accumulate on foliage, resulting in evaporation and a reduction in throughfall to the soil. Rainfall and dew replenish the subsurface moisture store that supplies the root water uptake. A multilayer soil and root system model incorporating hydraulic redistribution are used to compute moisture uptake through the root zone. At leaf-level scale, ecophysiological (photosynthesis and stomatal conductance) and physical (boundary layer conductance and energy balance) components are coupled to determine the flux densities of CO_2, water vapor, and heat as function of ambient environmental conditions and radiation drivers. Adapted from Drewry et al. (2010a). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

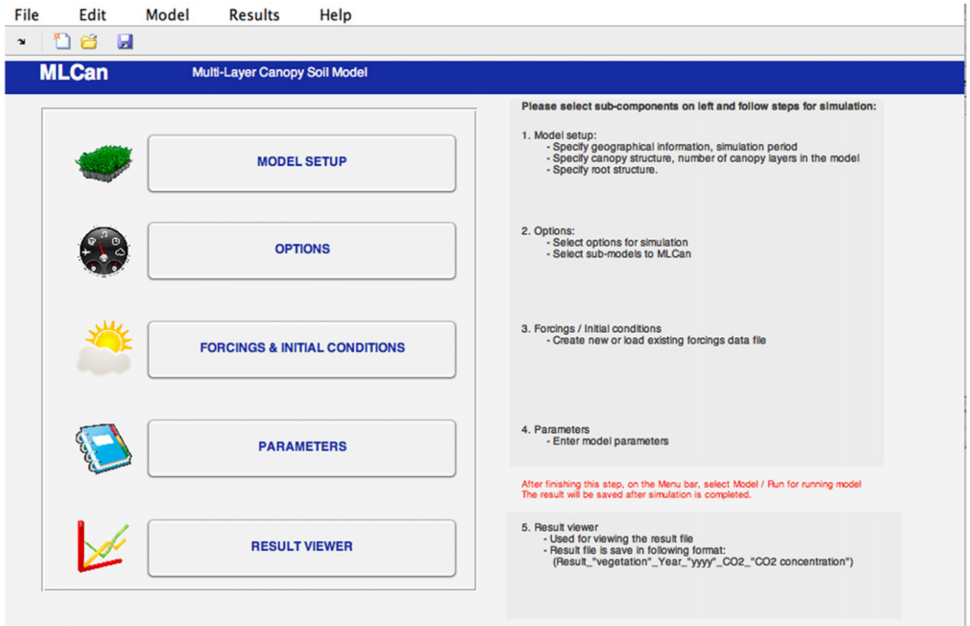

Fig. 2. Main window of the MLCan graphical user interface. Sub-components are organized by functions and tasks on the left and are also made available through menu bar. Corresponding instructions for each sub-components are presented on the right of the main window.

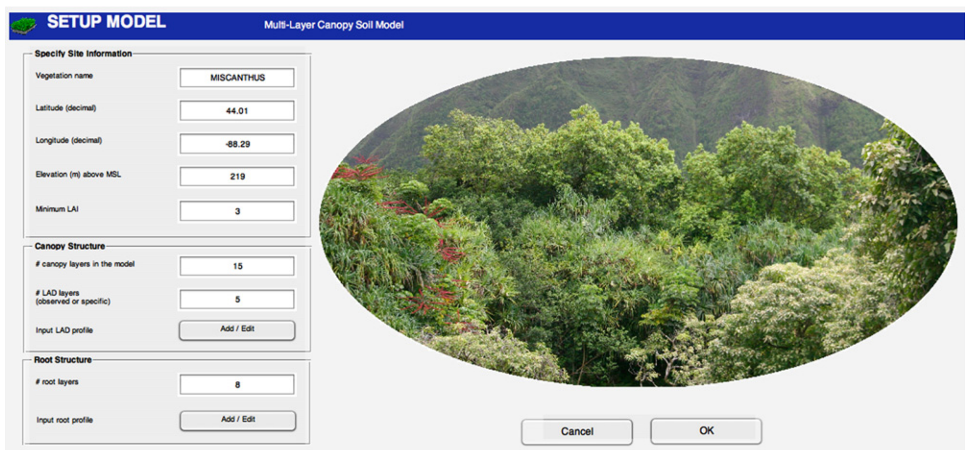

Fig. 3. View of *Model Setup* window. *Specify site information* panel is designed for setting up geographic location and plant species. Canopy and root structure panels are used for specification of structural characteristics of the above and below-ground systems. To support users, both canopy and root structure windows are plotting integrated.

formats include: text (*.txt), comma-separated values (*.csv), and Microsoft Excel (*.xls) files.

Similarly, the soil and root systems are also decomposed into multiple layers to resolve the vertical profiles of soil temperature and moisture content, as well as root water extraction (Drewry et al., 2010a). The distribution of the root through soil column is specified by users via one of two methods. First, a logistic dose–response curve developed by Schenk and Jackson (2002) can be selected. The two parameters representing 50% and 95% cumulative root distribution and one parameter for the maximum root depth are required for root distribution specification. Users can otherwise choose to specify the vertical root distribution manually via a table built into the GUI, or by uploading a data file analogously to canopy structure input.

2.2. Options

Model options and sub-models are selected by users in the *Option* window (Fig. 4). These model options are designed in the top four panels on the left side of this window. First, the *Photosynthesis* panel allows flexibility in the choice of vegetation photosynthetic pathway, C_3 or C_4. Second, the *Linear* option in the *Root Hydraulic Conductivity* panel allows for the specification of a linear decrease of root hydraulic conductivity (RHC) as a function of soil depth. If this option is not selected, no change of RHC with depth is applied. Third, the *Root Numerical Model* is used for selecting the numerical finite difference scheme in the root–soil model. Users can select either an *Explicit* or *Implicit* scheme (Durran, 1998) for the below-ground numerics (see also Quijano et al., 2012). Finally, atmospheric CO_2 concentration C_a is input via the CO_2 *concentration* panel. Two default C_a values for ambient (370 ppm) and elevated conditions (550 ppm) are given for reference. However, users can specify C_a values according to their specific needs.

There are three additional sub-models shown in the *Models* panel located at the bottom-left side of the *Options* window. Each sub-model is activated by checking a corresponding box. *Soil Heat Model* is used for simulating the heat transfer in the root–soil system. The ground heat flux is not only an important component

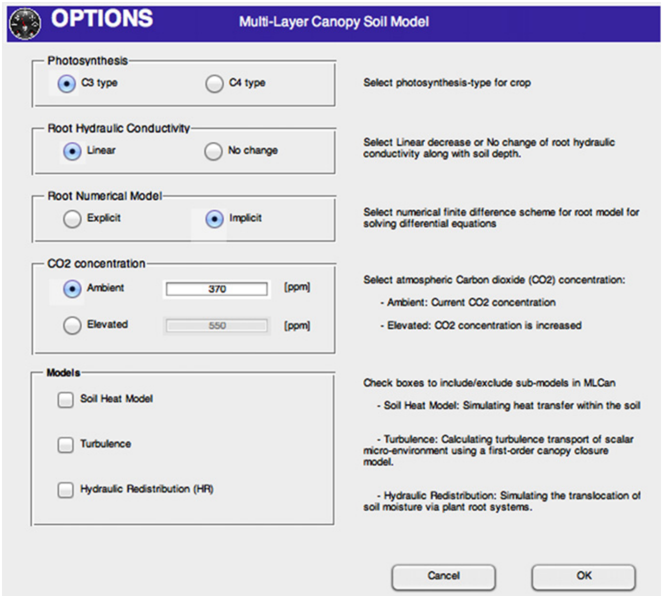

Fig. 4. View of model *Options* window. Users are allowed to select simulation modes and sub-models through a system of checkboxes and radio buttons. A short description for each option and model is shown on the right side of the window.

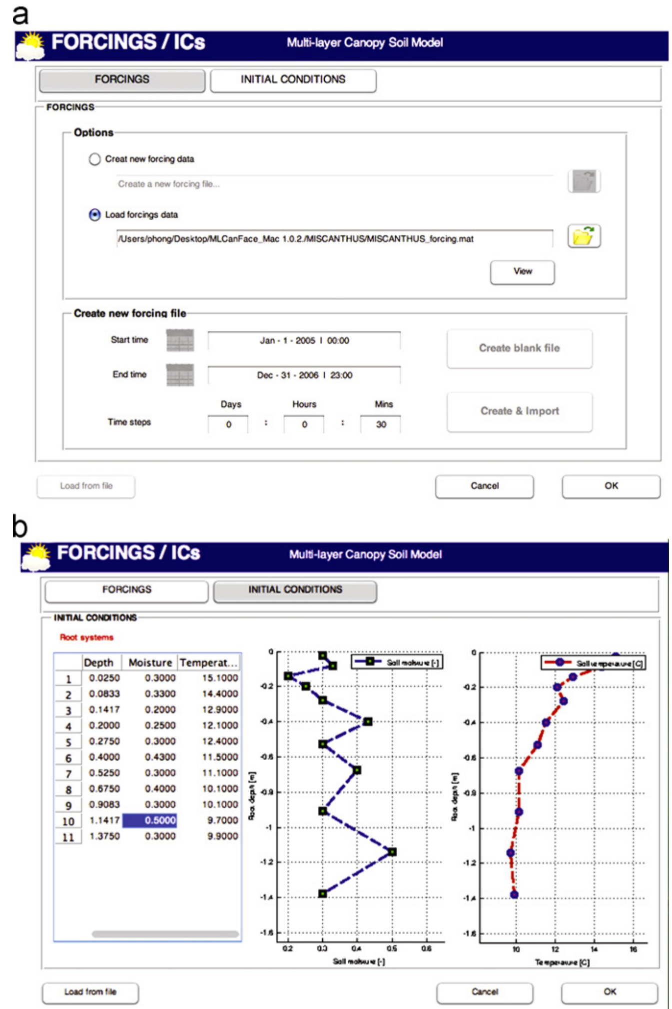

Fig. 5. View of model *Forcing* and *Initial Conditions* window. (a) The forcing tab is used for data processing. (b) The Initial Conditions tab is used for setting up initial conditions in the root–soil models.

of the surface energy balance (Yang et al., 1999) but also has a tight coupling with soil moisture (Small and Kurc, 2003). The *Turbulence* sub-model is applicable to calculate the turbulent transport of micro-environment space using a first-order canopy closure model (Poggi et al., 2004; Katul et al., 2004). Excluding *Turbulence* sub-model, the movement of scalar gradients within the canopy by eddy motions of the wind will be neglected in the main model. The *Hydraulic Redistribution* (HR) sub-model simulates the transfer of water by roots from moist to dry regions of the soil profile (Amenu and Kumar, 2008; Quijano et al., 2012). Short descriptions for options and sub-models are presented on the right of the *Option* window for supporting new users.

2.3. Forcings and initial conditions

The *Forcing* and *Initial Conditions* interface is designed to support and facilitate the specification of initial conditions and input of forcing data required to use MLCan. For convenience, this window is organized in two separate tab-pages as shown in Fig. 5.

The *Forcings* tab-page is provided for processing new input or loading existing data files (Fig. 5a) in MLCan. A flexible naming system with interface in MATLAB is included that allows users to save or select forcing files easily in the GUI. Error message boxes are integrated to redirect users as errors occur. We also integrate a calendar application for setting the time for simulation when users create a new forcing file. There are two options for processing new forcing data: (i) by choosing *Create blank file* button, users are allowed to create blank forcing files with appropriate temporal and spatial information obtained from other sub-components of the GUI, then they can use MATLAB to enter or transfer the observed forcing data to these blank forcing files; or (ii) users can import data directly from existing files by choosing the *Create and Import* button. A browsing window will appear to help users select appropriate files easily.

The *Initial Conditions* tab-page is designed for setting up initial conditions for soil moisture and temperature in the root–soil models. The vertical discretization in the below-ground system is obtained from the root profile shown in *Model Setup*. For better visualization, a built-in table and two interactive plots are integrated in this tab-page to display initial moisture and temperature throughout the depth of the soil column (Fig. 5b). Users can either input initial conditions manually or import automatically from existing data files.

2.4. Parameters

The specification of vegetation characteristics in MLCan is performed through the assignment of more than 40 parameter values, describing vegetation characteristics related to leaf geometry, biochemical and ecophysiological functioning, and soil properties. The *Parameters* window aims to organize these parameters into four separate tab-pages so that users can easily find them in the GUI (Fig. 6):

(i) *Leaf* and *canopy*: Parameters for describing leaf types and the physical characteristics of the canopy system. While the parameters for leaf types and shapes have impacts on latent heat, sensible heat, and long wave emission, the parameters for physical characteristics of the canopy strongly influence the within canopy regimes as well as water interception;

(ii) *Soil* and *radiation*: Parameters for describing soil characteristics and factors that relate to the radiation. These parameters play a fundamental role in the thermal and radiation regimes within the canopy and soil systems;

(iii) *Photosynthesis*: Photosynthetic parameters for C_3 and C_4 plants. Only one table in photosynthesis tab-page is enabled,

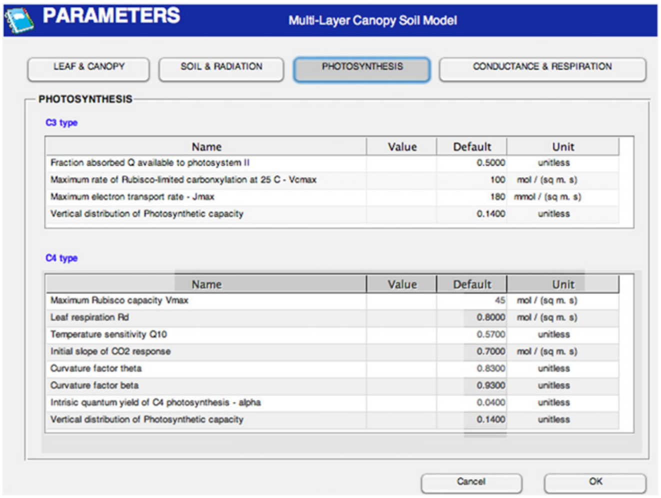

Fig. 6. View of *Parameters* window. Parameters are categorized in four tab-pages.

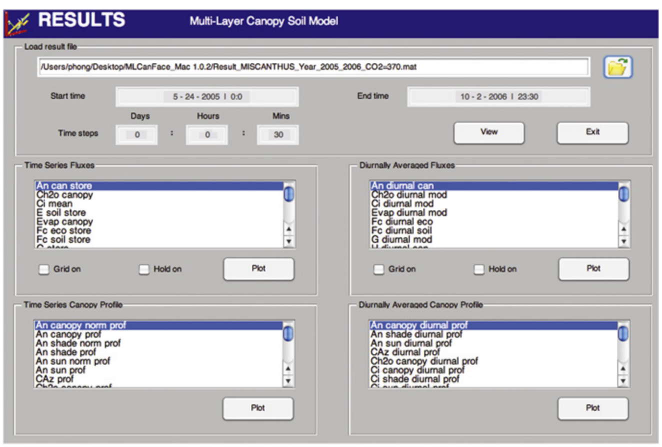

Fig. 7. *Result Viewer* window in the GUI. Four plotting modes are provided to examine corresponding interested variables.

depending on the user's selection for photosynthesis model in *Options* window;

(iv) *Conductance* and *respiration*: Parameters representing the values of respiration, leaf conductance, and micro-environment coefficients. These parameters are used for estimation of stomatal conductance in the Ball–Berry model (Ball et al., 1987).

In addition, parameters for maize (*Zea mays*), a C_4 plant, validated by Drewry et al. (2010a) are provided for reference in the GUI. Definitions and more elaborate descriptions of required parameters in MLCan model are presented comprehensively by Drewry et al. (2010a). We refer interested users to that paper for further information.

2.5. Result viewer

An independent *Result Viewer* interface is developed in this GUI to allow users to easily visualize and analyze numerical results obtained from MLCan. The window of this *Result Viewer* is presented in Fig. 7. At the very top, a browsing window is designed to allow users to select an output file. Additional information in the *Load result file* panel shows the name of the working file, time step, and simulation periods (Fig. 7).

There are four view modes designed for users to examine a wide range of output variables. First, the *Time Series Fluxes* panel plots single time series from the beginning to the end of the simulation period. Second, the *Diurnally Averaged Flux* panel plots the single diurnal variations of variables (over the course of the day) with vertical bars representing $\pm$ one standard deviation. Diurnally average values are the mean values of variables that have the same diurnal time during the simulation period. Standard deviation represents the variability of data at the specific time away from their diurnally averaged value. Next, the *Time Series Canopy Profile* plots the within-canopy profiles of fluxes or variables from the beginning to the end of the simulation period. Finally, the *Diurnally Averaged Canopy Profile* plots the diurnally averaged canopy profiles simulation period. The use of this *Result Viewer* for analyzing model results is illustrated in two case studies shown in the next section.

3. Example simulations

To further demonstrate the use and capabilities of the MLCan GUI for exploring the eco-hydrological responses of vegetation to environmental forcings, simulations for three bioenergy crops at two different sites in the Midwestern United States are presented.

3.1. Background

Lignocellulosic bioenergy is being considered as a promising alternative for starch-based bio-ethanol to meet renewable fuel targets (Hess et al., 2003). In the Midwestern United States, C_4 perennial grasses such as miscanthus (*Miscanthus* $\times$ *giganteus*) and switchgrass (*Panicum virgatum*) are being considered as the two lignocellulosic feedstocks with the greatest potential biofuel yield per unit land area, reduced requirement of nutrient inputs (Heaton et al., 2008, 2004), and low net CO_2 emissions (Liebig et al., 2008; Clifton-Brown et al., 2007; Ma et al., 2000). Therefore, it is likely that a large portion of the agricultural landscape, e.g. land that supports maize (*Zea mays*) production, in the Midwestern United States will be converted to these crops for meeting future bioenergy demands.

Recent works have highlighted the potential impacts of these land-use conversions on the hydrologic cycle and climate in the US Midwest (Le et al., 2011; Georgescu et al., 2011). In the study by Le et al. (2011), data from a single site at Bondville, Illinois in the 2005 growing season was used to validate the MLCan model for miscanthus and switchgrass. The eco-hydrological responses of these two crops were contrasted with maize to explore the

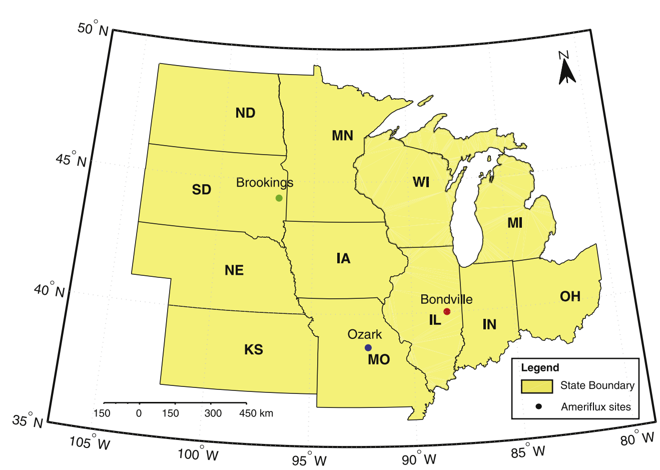

Fig. 8. Map of Ameriflux towers located at Bondville, Illinois (red dot); Ozark, Missouri (blue dot); and Brookings, South Dakota (green dot) in the Midwestern United States. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

potential hydrologic change associated with land conversion to bioenergy crops in the Midwest. The findings showed that both miscanthus and switchgrass utilize more water than maize under the same climate conditions due to their high biomass productivity and longer growing seasons, raising the water stress concerns for large-scale advanced bioenergy production. It also highlighted the importance of weather and climate variability on the eco-hydrological responses of vegetation cover.

In these illustrated case studies, we further expand the work of Le et al. (2011) to two other locations in the Midwest for exemplifying the use of this GUI for the MLCan model. In addition, we use the GUI to examine the role of spatial climate variability on the hydrologic change associated with these land conversions across the Midwest US. The available model also includes parameter sets for soybean and Ponderosa Pine (see Drewry et al., 2010a, 2010b; Quijano et al., 2012 for related studies).

3.2. Materials and methods

We separately ran the MLCan model using the GUI in order to simulate the ecohydrological responses of three crops (maize, miscanthus, and switchgrass) at two sites located in Ozark,

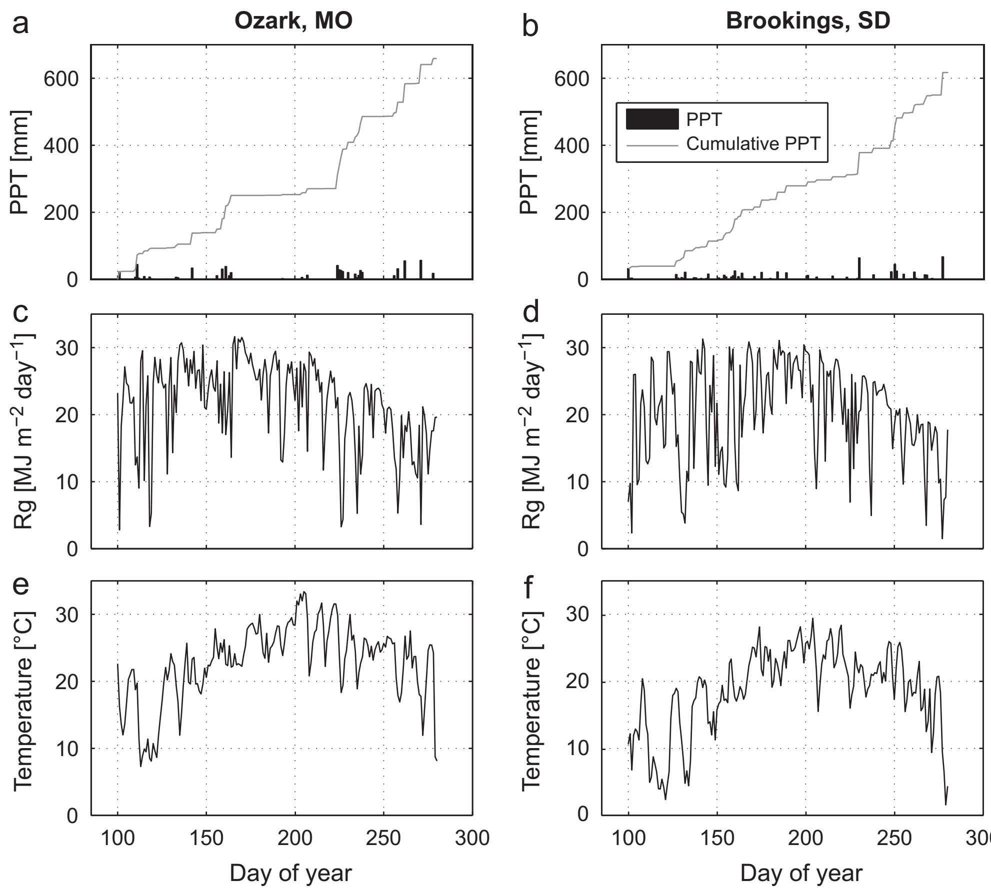

Fig. 9. Key meteorological forcing data observed on Ameriflux towers at Ozark, MO (a, c, e) and Brookings, SD (b, d, f) in growing season 2005. Meteorological data includes daily and cumulative precipitation *PPT*; daily global radiation *Rg*; and mean daytime air temperature *Ta*.

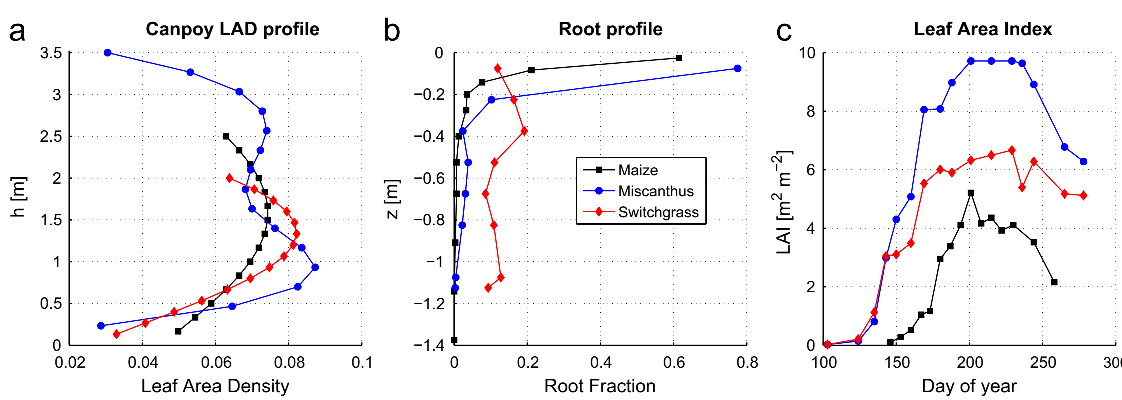

Fig. 10. Structural characteristics and ecophysiological data for maize, miscanthus, and switchgrass. (a) Canopy leaf area density profiles, (b) root fraction in each soil layer, and (c) leaf area index in growing season 2005 for maize (black squares), miscanthus (blue circles) and switchgrass (red diamonds). Adapted and modified from Le et al. (2011); data is obtained from Drewry et al. (2010a), Monti and Zatta (2009), Kromdijk et al. (2008), Madakadze et al. (1998). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

Missouri (38.74°N, 92.20°E) and Brookings, South Dakota (44.34°N, 96.84°E). We then compare the water utilization at each site to investigate the crop impacts on the hydrologic cycle. Moreover, water utilization of each crop at two sites are compared with those at the original site at Bondville, Illinois (40.01°N, 88.29°E) (Le et al., 2011) to understand the effect of spatial climate variability on the hydrological impacts. A map showing the locations of these threes site is presented in Fig. 8. For data and results at the Bondville site, readers are referred to the study by Le et al. (2011). Here we only present results obtained for the Ozark and Brookings sites. All simulations at the three sites are implemented during the same period in the growing season 2005 (day of year 143rd–278th) for comparison.

Measurements of half-hourly meteorological data were obtained from nearby Ameriflux towers (http://public.ornl.gov/ameriflux) located at these sites for forcing inputs. Key meteorological forcing data observed in growing season 2005 for Ozark and Brookings is shown in Fig. 9, demonstrating slightly different climate conditions between the two locations. All of sub-figures for forcing inputs and numerical results can be produced separately using appropriate plotting types in the *Result Viewer* of the GUI. For purpose of concise illustration, these sub-figures

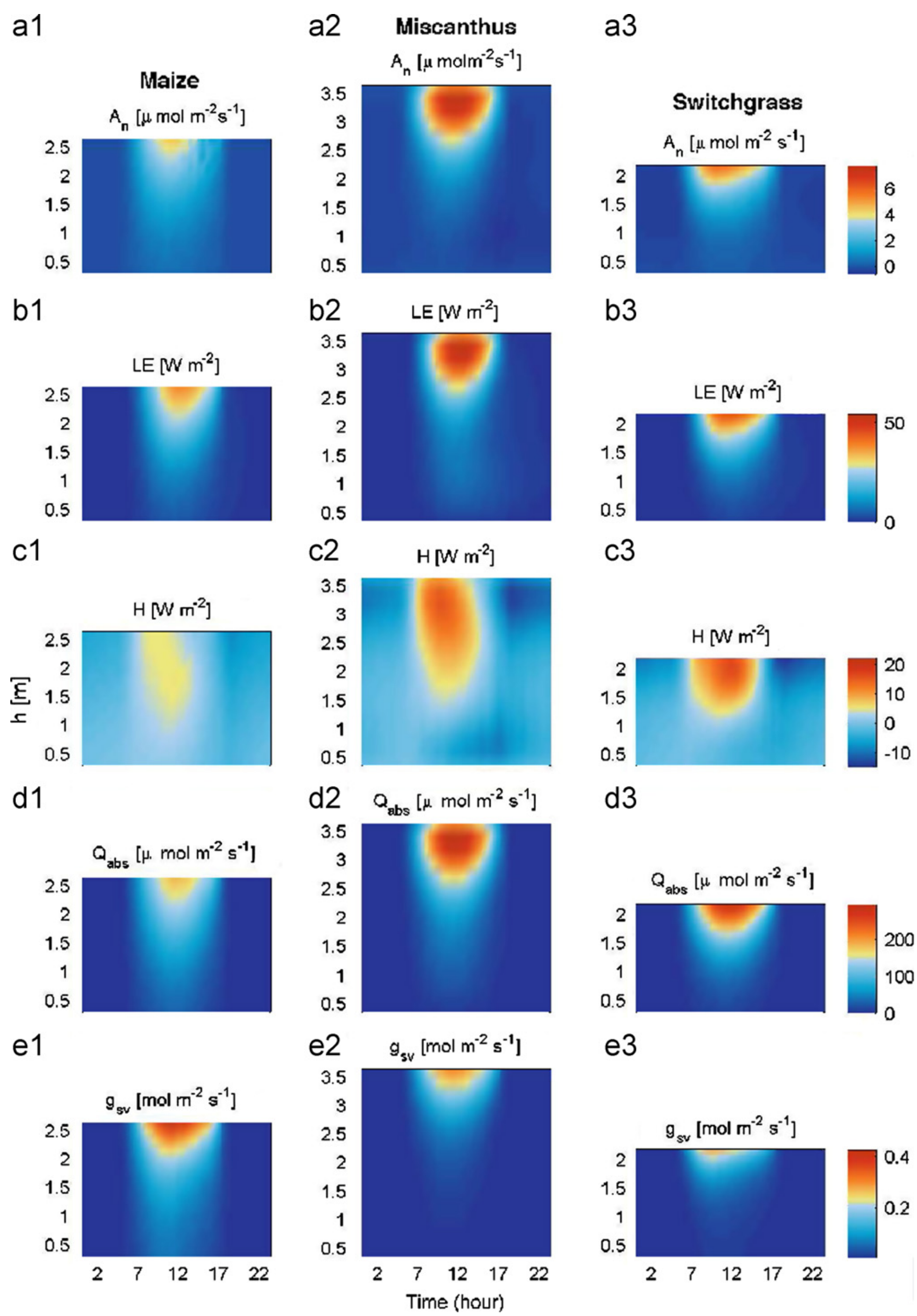

Fig. 11. Diurnally averaged profiles obtained from MLCan model simulation under climate condition in Ozark, Missouri in August 2005 for photosynthetic rate A_n; latent heat *LE*; sensible heat *H*; total absorbed shortwave radiation included photosynthetically active and near-infrared bands Q_{abs}; and stomatal conductance for vapor g_{sv} for maize (left column – a1, b1, c1, d1, and e1), miscanthus (center column – a2, b2, c2, d2, and e2), and switchgrass (right column – a3, b3, c3, d3, and e3).

are grouped and combined into single figures in this paper. Specification of the structural characteristics of the canopy (Fig. 10a), root and soil systems (Fig. 10b) for three crops are similarly constructed as shown in study by Le et al. (2011). We use leaf area index (LAI) data from the study by Heaton et al. (2008) for miscanthus and switchgrass and the study by Drewry et al. (2010a) for maize observed in central Illinois since there is no observation of these crops at those two locations. Variations of interpolated daily LAI for three crops in growing season 2005 are presented in Fig. 10c. Miscanthus and switchgrass show much higher values of LAI than maize, highlighting their potential for lignocellulosic bioenergy production. Moreover, their growing seasons are also longer than maize. These characteristics imply a potential impact on the hydrologic cycle under extensive areal land-use change in the region. Parameterization and validation for the three crops follow those previously

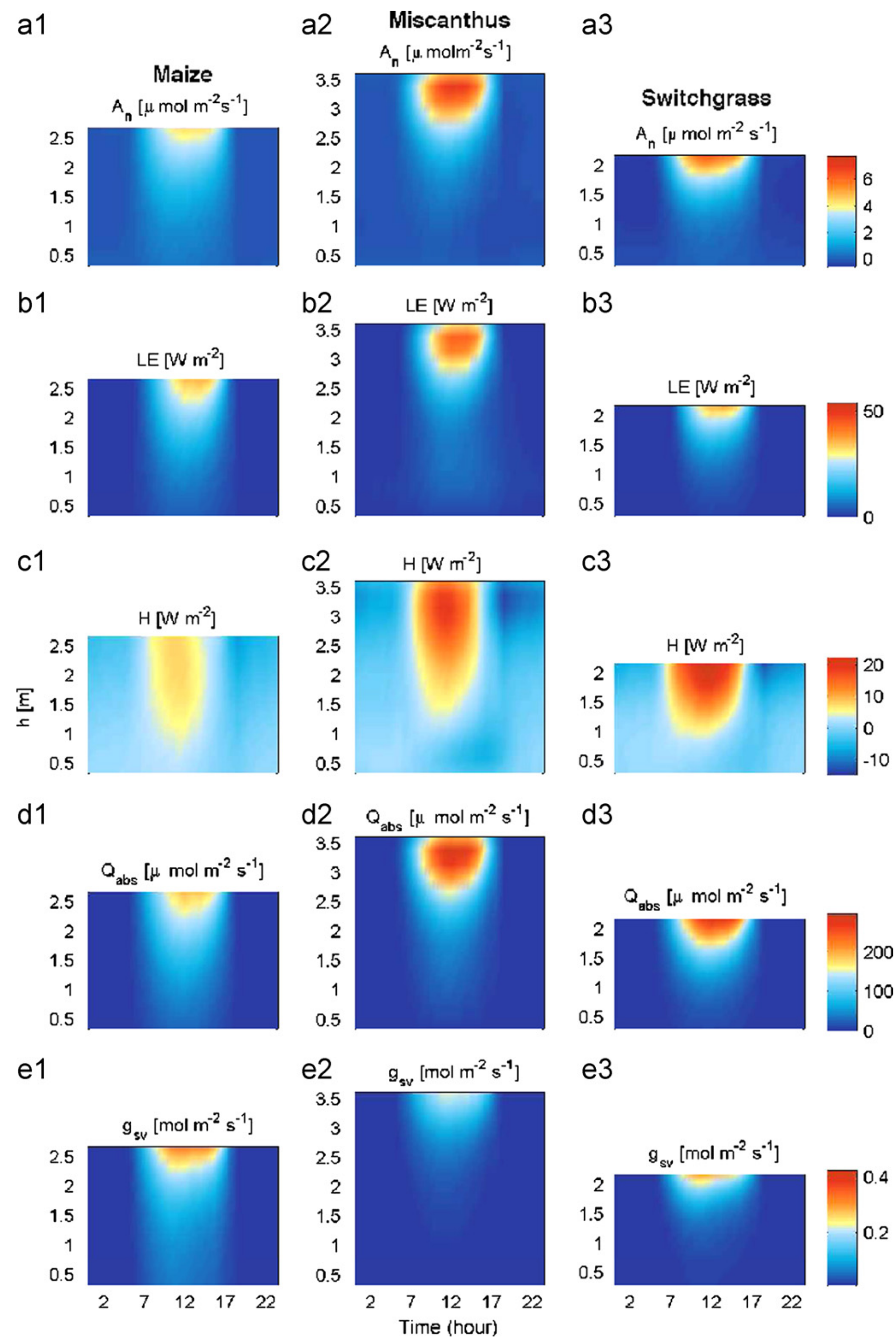

Fig. 12. Diurnally averaged profiles obtained from MLCan model simulation under climate condition in Brookings, South Dakota in August 2005 for photosynthetic rate A_n; latent heat LE; sensible heat H; total absorbed shortwave radiation included photosynthetically active and near-infrared bands Q_{abs}; and stomatal conductance for vapor g_{sv} for maize, miscanthus, and switchgrass. Notations and symbols are similar to Fig. 10.

presented by Drewry et al. (2010a) and Le et al. (2011). Site-independent parameters from those studies are used and imported to the *Parameters* component of the GUI for running the model.

3.3. Results and discussions

The *Result Viewer* in this GUI is used to present and analyze numerical results obtained from the main model for bioenergy crops. These analyses provide insights into the impact of vertical distribution of leaf area and root biomass of these crops on within canopy and soil processes at multiple layers and understanding on the net-canopy flux exchanges between the land surface and the atmosphere

The output visualization capability of the MLCan GUI is demonstrated in Figs. 11 and 12 through the generation of figures showing within-canopy variability over mean diurnal time periods. Fig. 11 presents the mean diurnal vertical patterns of

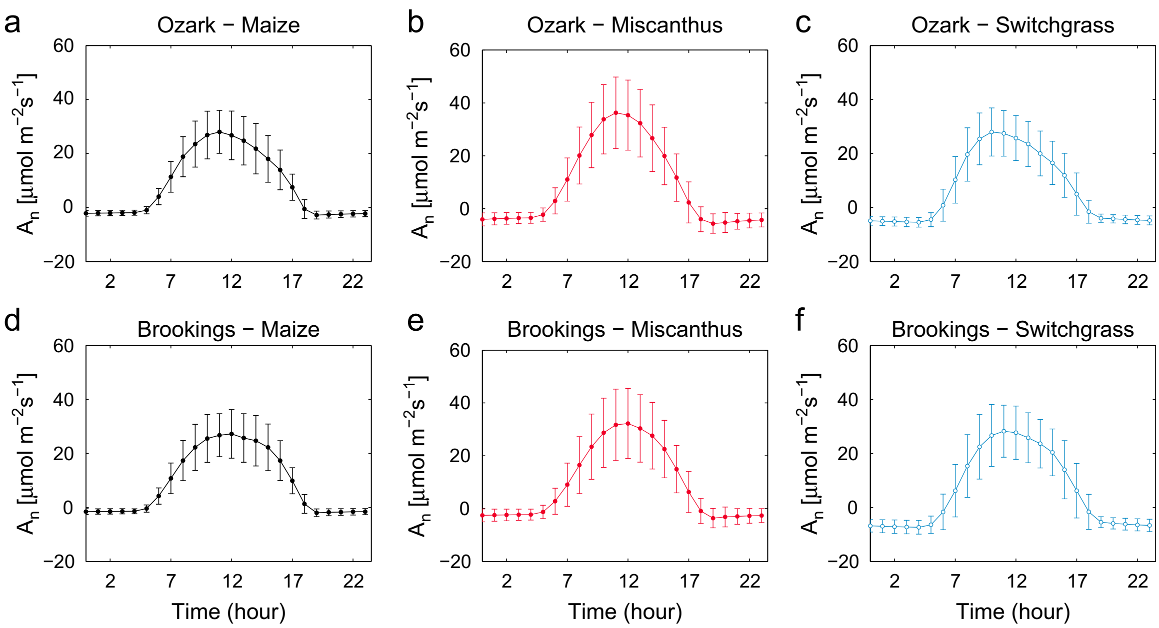

Fig. 13. Diurnally averaged net-canopy fluxes of A_n obtained from the MLCan model at Ozark (a, b, c) and Brookings (d, e, f) sites with vertical bars representing ± one standard deviation over one growing season in 2005 for maize (black), miscanthus (red), and switchgrass (blue). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

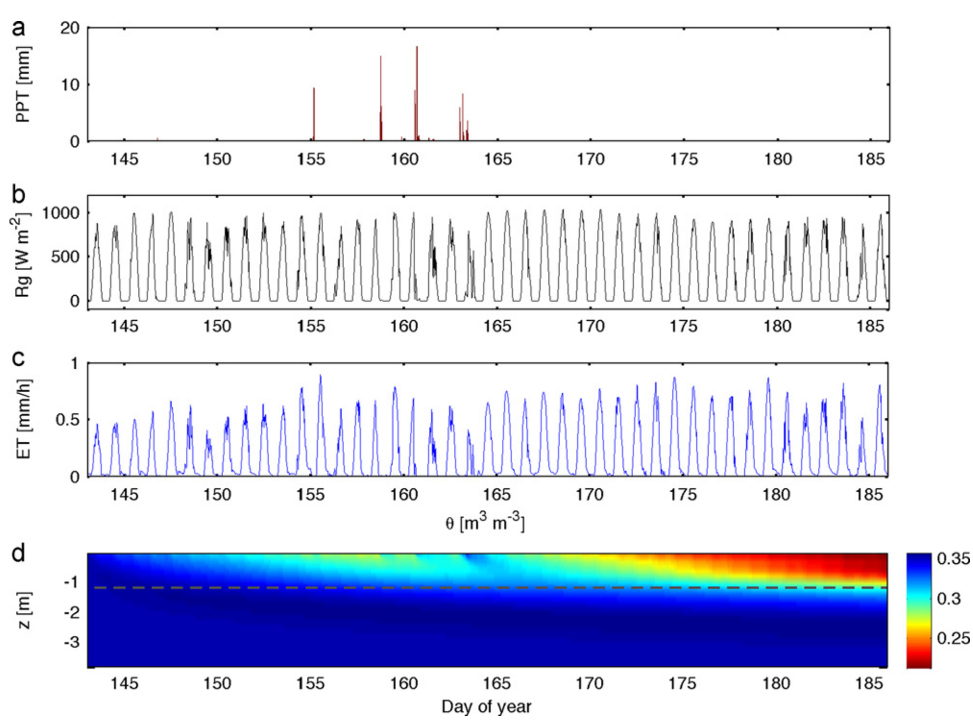

Fig. 14. Diurnal variations of fluxes and soil moisture profile for miscanthus during a 40 day period in growing season 2005 at Ozark site. (a) precipitation *PPT*, (b) incoming shortwave radiation *Rg*, total evapotranspiration *ET*, and (d) soil moisture through the modeled soil column with the depth of the root zone denoted by a dashed gray line.

photosynthetic leaf CO_2 uptake (A_n), latent heat flux (LE), sensible heat flux (H), total absorbed shortwave radiation including photosynthetically active (PAR) and near-infrared (NIR) bands (Q_{abs}), and stomatal conductance for vapor (g_{sv}) through the canopy for three crops over the month of August, 2005 at Ozark site. Fig. 12 presents the same information for Brookings site. These distributions show the mean values of fluxes and variables over the course of the day, averaged over the entire simulation period. For each crop at both sites, the distributions of A_n and LE correspond closely to Q_{abs}, similar to those in Bondville (Le et al., 2011), highlighting the important role of PAR on A_n and Q_{abs} on LE (Drewry et al., 2010a). However, source areas of H located deeper in the canopy than those of A_n and LE indicate the ability of NIR to penetrate deeper into the canopy as well as the shallow distribution of g_{sv} that represents the stomatal opening for canopy transpiration and photosynthesis. Indeed, the greatest values of g_{sv} are located at the very top of the canopy where shortwave intensity is strongest.

At each study site, the distributions of these variables among three crops are different, demonstrating the impact of LAI and vertical LAD on within canopy processes. Switchgrass and maize have a more uniform LAD profiles than that of miscanthus, which in combination with their lower LAI, result in more uniformly distributed radiation regimes throughout the canopy. In contrast, miscanthus has a much denser canopy with higher LAI that more effectively shades the soil column below it and increases interception of precipitation and condensation, potentially affecting the soil moisture state. Moreover, the distributions of all variables vary slightly among these two sites and the Bondville site showing the impact of meteorological forcing data on the responses of vegetation.

Canopy-scale fluxes exchanged between the land surface and atmosphere are computed through the vertical integration over each of the foliage layers. Fig. 13 shows the diurnally averaged net-canopy fluxes of A_n obtained from MLCan model for three crops with vertical bars representing ± one standard deviation

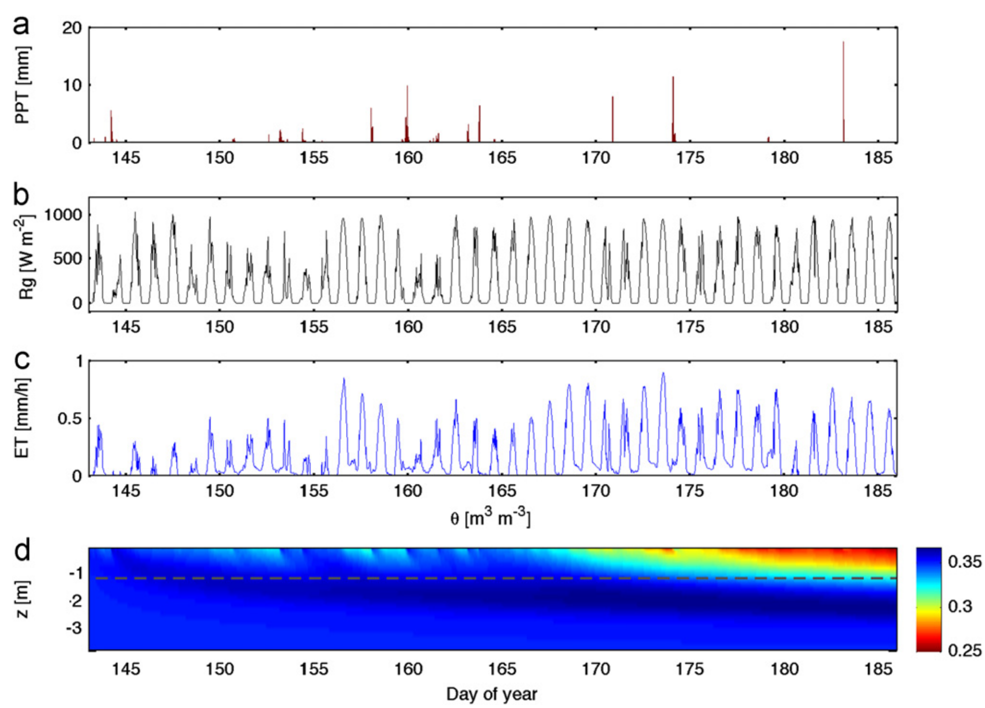

Fig. 15. Diurnal variations of fluxes and soil moisture profile for miscanthus during a 40 day period in growing season 2005 at Brookings site. Notations and symbols are similar in Fig. 13.

Table 1
Comparison of total evapotranspiration (ET) and its component contribution maize, miscanthus, and switchgrass in growing season 2005 (results at Bondville are obtained from Le et al., 2011).

Crops		Maize	Miscanthus	Switchgrass
Total ET (mm)	Bondville	380	588	498
	Ozark	389	607	533
	Brookings	378	541	462
Transpiration (mm)	Bondville	302 (82.4%)	473 (80.5%)	402 (80.7%)
	Ozark	306 (78.7%)	511 (84.2%)	435 (81.6%)
	Brookings	292 (77.2%)	438 (81.0%)	369 (79.9%)
Canopy evaporation (mm)	Bondville	36 (9.4%)	98 (16.6%)	66 (13.3%)
	Ozark	32 (8.2%)	82 (13.5%)	62 (11.6%)
	Brookings	23 (6.1%)	77 (14.2%)	53 (11.5%)
Soil evaporation (mm)	Bondville	42 (11.2%)	17 (2.9%)	30 (6.0%)
	Ozark	51 (13.1%)	14 (2.3%)	36 (6.8%)
	Brookings	63 (16.7%)	26 (4.8%)	40 (8.6%)

over the growing season in 2005 at Ozark and Brooking sites. Compared to maize and switchgrass, consistently higher A_n values of miscanthus imply stronger photosynthetic CO_2 uptake of miscanthus than other two crops during the growing season which is strongly related to the crop water use. The standard deviation bars also represent more variability of A_n in miscanthus than in maize and switchgrass.

Figs. 14 and 15 present the variations of precipitation, total evapotranspiration (ET) and simulated moisture through the soil column during a 40 day period in the growing season 2005 at Ozark and Brookings sites, respectively. While precipitation affects the soil moisture state by adding throughfall to the top soil layers, incoming radiation is the primary driver for ET, which results in water losses from the soil column. Total water use of three crops in growing season 2005 are unequal from site to site (Table 1) due to the impacts of climatic gradient. At higher altitude with lower air temperature and incoming shortwave intensity, water use of corresponding crops in Brookings is lower than that at the two other sites. In contrast, water use in Ozark is largest, highlighting the impact of air temperature and incoming radiation on *ET*.

4. Conclusions

Vertically discretized canopy models can provide new insights in our understanding of land–atmosphere interactions and potentially provide greater accuracy in predictions of the impact of future climate change on the biosphere and terrestrial water cycle. A graphical user interface developed for a multilayer canopy–soil–root system model (MLCan) (Drewry et al., 2010a) was described. Important features with basic functionalities written in MATLAB were shown. The development of this GUI aims to simplify the use of this model and make it available to a broader set of interested users.

Application of the GUI for investigating the ecohydrologic responses of three bioenergy crops to the surrounding environment at two locations in the Midwest was illustrated. The results shown in this study confirm the potential impacts of lignocellulosic bioenergy crops (miscanthus and switchgrass) on the hydrologic cycle in the Midwest. Compared to maize, larger LAI values and difference in canopy and root structures of miscanthus and switchgrass results in significantly increased transpiration and direct evaporation on foliage, thereby affecting the soil moisture profile. For large-scale bioenergy production, these issues should be considered with other benefits for sustainability.

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