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Estimating Water Use Efficiency in Bioenergy Ecosystems Using a Process-Based Model

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30.1. INTRODUCTION

Bioenergy, made available from materials derived from biological sources, has been widely considered as one of the major renewable and sustainable energy sources to enhance energy security and mitigate climate change [*Beringer et al.*, 2011; *Fargione et al.*, 2010]. Food grain is currently the most popularly used biomass feedstock for biofuel production, e.g., maize (*Zea Mays* L.) grain for bioethanol and soybeans [*Glycine max* (L.) Merr.] for biodiesel. However, traditional biofuels have many unintended consequences concerning feedstock availability, food security, environmental sustainability, and societal welfare. During the last two decades, maize grain production increased about 65%. The major contribution is from grain yield, with about 1.96% increase annually [*FAOSTAT,* 2012]. But most of maize grain in the United States is used for human consumption, livestock feed, or other purposes. Only about 30% of grain harvested was used for ethanol production in 2009 [*USDA,* 2010]. The slowly growing maize production may not be able to support the rapidly increasing biofuel demand. Food-based feedstocks alone may limit further biofuel expansion, for instance, to reach the 2022 U.S. biofuel target [*U.S. Congress,* 2007]. In addition, conventional food-based biofuel development can be a threat to food security, due to competitive consumption of cropland, water, and nutrient resources that could otherwise be used for food production [*Fargione et al.*, 2010]. Indirect land use impacts on ecosystem services, such as monoculture and deforestation, also limit further expansion of conventional biofuel development [*Fargione et al.*, 2010; *Searchinger et al.*, 2008].

Second-generation biofuel (or advanced biofuel), produced from various types of biomass, is increasingly recognized as another option for bioenergy development. Among many tested species, switchgrass (*Panicum virgatum* L.) and *Miscanthus* (e.g., *Miscanthus giganteus*) were often studied for its characteristics, adaptation, and environmental impacts in the United States [*Fargione et al.*, 2010; *Heaton et al.*, 2008; *McIsaac et al.*, 2010]. Switchgrass is a perennial, warm-season cellulosic crop native to North America. It is widely distributed over the United States, especially the prairies of the Midwest [*Wright and Turhollow*, 2010]. Switchgrass was originally used for soil conservation, forage production, and other purposes. It is more recently used as biomass crop for biofuel production and electricity and heat production [*McLaughlin and Adams Kszos*, 2005; *Meyer et al.*, 2010]. *Miscanthus* is a genus of several species of perennial grasses mostly native to subtropical and tropical regions of Asia. It was used as biofuel crop in Europe since the 1980s and then introduced to the United States recently [*Heaton et al.*, 2008; *Stewart et al.*, 2009]. Several commonly shared characteristics make switchgrass and *Miscanthus* favorite choices as biofuel feedstock resources. First of all, they can produce abundant biomass, with much higher production than maize or soybeans. It normally ranges from 5 to 15 Mg dry matter (DM)/ha^{-1} with maximum production of over 20 Mg DM/ha for switchgrass, and about 20–30 Mg DM/ha with maximum of 60 Mg DM/ha for *Miscanthus* [*Heaton et al.*, 2008;

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Wright and Turhollow, 2010]. In addition, these cellulosic crops have high input use efficiency. They are perennial rhizomatous plants, capable of cycling nutrients seasonally between the above- and below-ground vegetation, and thus minimizing fertilizer application. It was reported that switchgrass and especially *Miscanthus* require no or very small amounts of nitrogen (N) fertilizer, if any, while maize growth may double or even triple the N demand [*Fargione et al.*, 2010; *Lewandowski et al.*, 2003]. Switchgrass and *Miscanthus* are C4 plants and therefore normally more photosynthetically efficient than C3 plants (e.g., soybeans) [*Heaton et al.*, 2004; *Skinner et al.*, 2012]. Also, the agronomic management for these cellulosic crops is relatively less sophisticated and more energy saving than food crops. Planting is required only once, and fertilization or tillage is less frequently needed [*Skinner et al.*, 2012]. Compared with maize, these crops may potentially release less life-cycle greenhouse gases due to less N fertilizer application [*Hillier et al.*, 2009; *Skinner et al.*, 2012].

However, conversion of food crops to cellulosic crops for biofuel production will likely alter carbon (C), N, and more importantly water dynamics, which may eventually impact the water use efficiency in terms of C production per unit of water loss. Earlier studies from either field observations [*Heaton et al.*, 2008; *Wright and Turhollow*, 2010] or model simulations [*Qin et al.*, 2012] showed that cellulosic crops (e.g., *Miscanthus*) could have higher biomass productivity than food crops (e.g., maize). Also, there was evidence indicating that cellulosic crops may use more water than food crops to produce biomass. For instance, a field experiment conducted in Urbana, Illinois, indicated that evapotranspiration from *Miscanthus* was about 104 mm/yr greater than under maize-soybean [*McIsaac et al.*, 2010]. Modeling experiments also suggested that *Miscanthus* consumes more water than maize in order to support crop growth (e.g., [*VanLoocke et al.*, 2010; *Zhuang et al.*, 2013]). It is therefore important to assess water use efficiency to relate biomass production to water consumption.

In order to evaluate regional or national impacts of bioenergy expansion on carbon-water relationship, large-scale models are required to incorporate spatially explicit information of climate, soil, and vegetation [*Le et al.*, 2011; *Vanloocke et al.*, 2010]. In ecosystem models, C and N dynamics are normally simulated to assess biomass production, C exchange, and possibly greenhouse gas emissions. Hydrology components, if available in the model, can be applied to simulate water cycle at large scales. The hydrological simulation together with biomass and C simulation will further be used to estimate regional water balance and water use efficiency [*Le et al.*, 2011; *VanLoocke et al.*, 2010]. For a given region, the amount of biomass production, ecosystem C balance, and biofuel production relative to the amount of water used can be used to interpret water use efficiency at different scales and for different purposes [*VanLoocke et al.*, 2012; *Zhuang et al.*, 2013]. In this study, the main goal is to assess water balance and water use efficiency of different crop ecosystems over the conterminous United States. It is assumed that conventional grain crop, maize, and two cellulosic crops, switchgrass and *Miscanthus*, will be grown on current maize cropland as potential energy crops for biomass production. By using an extended ecosystem model, we propose: (1) to estimate spatially explicit ecosystem productivity and water balance and (2) to assess water use efficiency of ecosystem production, in terms of biomass production and ecosystem C balance with regard to ecosystem water loss.

30.2. MATERIALS AND METHODS

30.2.1. Overview

In order to produce biofuel from biomass feedstocks, conventional maize, switchgrass, and *Miscanthus* can be grown on current maize-producing areas. In the conterminous United States, maize is traditionally considered as food crop, but a considerable proportion of its grain was devoted to ethanol production since the late 2000s. Switchgrass and *Miscanthus* are widely considered as possible alternatives to maize as energy crops in the temperate regions and can be potentially grown on croplands due to their adaptability to different soil and climate environments [*Davis et al.*, 2012; *Fargione et al.*, 2010; *Heaton et al.*, 2004]. A biogeochemical model was used to simulate biomass production and corresponding water dynamics for separate crop ecosystems.

A well-documented process-based model, the Terrestrial Ecosystem Model (TEM), coupling with a hydrological model was first described with emphasis on C dynamics and hydrology. Then, TEM was calibrated and extrapolated to specific regions (i.e., maize-producing areas) to simulate grid-by-grid C fluxes and pools, water balance, and water use efficiency, using spatially referenced data describing local climate, soil, and vegetation characteristics. Finally, spatial analyses were conducted to assess national biomass production, ecosystem C exchange, water consumption, and water use efficiency.

30.2.2. Model Description and Parameterization

TEM is a global-scale ecosystem model, originally designed to estimates C and N fluxes and pool sizes in terrestrial ecosystems at a monthly time step using spatial climate and ecological data [*McGuire et al.*, 1992; *Raich et al.*, 1991]. The model has been updated and

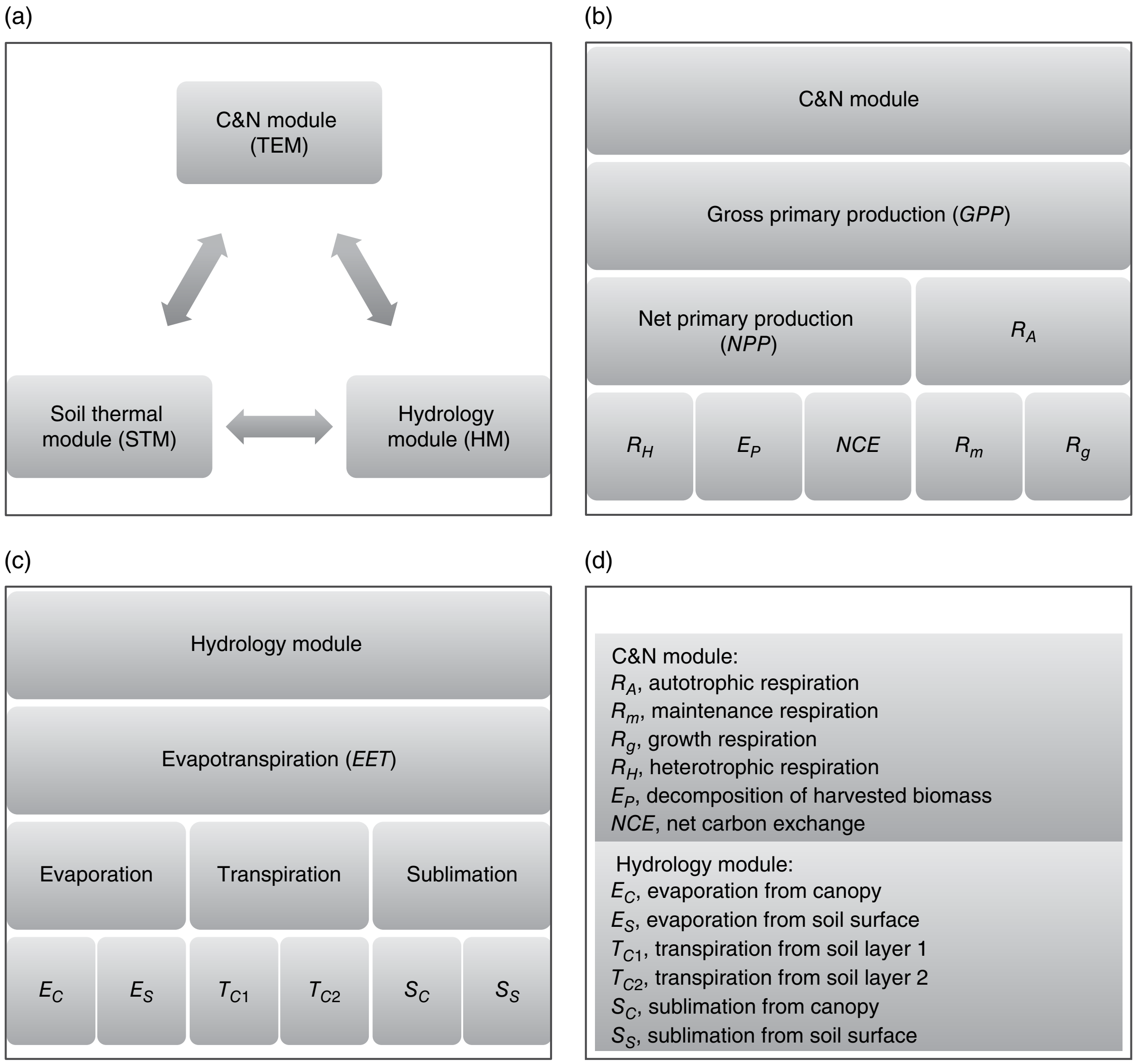

Figure 30.1 Terrestrial Ecosystem Model. (a) The TEM version used in this study includes the core C&N module (original TEM), as well as STM and HM modules. (b) Sketch of carbon allocation in TEM. (c) Sketch of EET modeling in the HM framework. (d) Variable abbreviations in the modules. Transpiration is split into T_{C1} and T_{C2} according to soil layers; sublimation would be considered if snowfall present.

further developed to integrate more up-to-date knowledge and algorithms for different simulating purposes [*Felzer et al.*, 2004; *Melillo et al.*, 2009; *Zhuang et al.*, 2003, 2010]. The TEM version used in this study includes the core module of TEM describing C and N dynamics, the soil thermal module simulating soil thermal dynamics, and a hydrological module of terrestrial ecosystems (Figure 30.1a).

In TEM, the C and N cycles are simulated by dividing the total ecosystem C and N stock into separate vegetation and soil pools, and simulating C and N dynamics using multiple flux variables. Of these fluxes, gross primary production (GPP) is the governing variable describing the rate at which the plant produces useful chemical energy. GPP can be further split into autotrophic respiration, which indicates energy loss due to plant growth and maintenance, and net primary production (NPP), which represents the rate of net "useful" energy produced by an ecosystem's producers (e.g., forest, grass) (Figures 30.1b and 30.1d). In TEM, GPP is modeled as a function of the maximum rate of C assimilation (C_{MAX}) and multivariate factors:

$$\mathrm{GPP} = \mathrm{C}_{MAX} \cdot \prod f(X_i), \tag{30.1}$$

where $f(X_i)$ is a scalar used to simulate impacts of physiological, biogeochemical, or environmental variable or process X_i on GPP. The X_i's in TEM include, but are not limited to, factors such as irradiance of photosynthetically active radiation, atmospheric CO_2

concentration, relative canopy conductance, air temperature, moisture, and nitrogen availability [*McGuire et al.*, 1992; *Raich et al.*, 1991]. NPP is mostly referred to as net biomass production of an ecosystem in terms of carbon fixation rate. It is modeled as the difference between GPP and autotrophic respiration. The net carbon exchange (NCE) between the terrestrial biosphere and the atmosphere is described as the remaining C flux in NPP after heterotrophic respiration (R_H) and decomposition of harvested biomass (E_P) [equation (30.2)] [*McGuire et al.*, 2001]. NCE represents the net C flux at the ecosystem scale, with a positive value showing a CO_2 sink and a negative value showing a CO_2 source. In this study, only 30% of maize stover was collected for biofuel use, the rest was returned to soil to maintain soil fertility [*Payne*, 2010]:

$$\mathrm{NCE} = \mathrm{NPP} - R_H - E_P. \tag{30.2}$$

The hydrological cycle in TEM consisted of processes of precipitation (rainfall and snowfall), sublimation, evaporation, interception, throughfall, percolation, transpiration, runoff, and drainage [*Zhuang et al.*, 2002]. Evapotranspiration is a significant water loss from ecosystem and mostly used to quantify water consumption of an ecosystem. In TEM, estimated evapotranspiration (EET) is calculated as a total of evaporation (E), transpiration (T) and sublimation (S):

$$\begin{aligned}\mathrm{EET} &= E + T + S \\ &= (E_C + E_S) + (T_{C1} + T_{C2}) + (S_C + S_S),\end{aligned} \tag{30.3}$$

where evaporation, transpiration, and sublimation are separately subdivided into multiple components according to canopy and soil layers (Figures 30.1c and 30.1d). In the model, EET is also constrained by potential evapotranspiration (PET) based on Jensen-Haise formulation [*Jensen and Haise*, 1963] and soil moisture [*Zhuang et al.*, 2002]. In crop ecosystems described in this study, EET simulated in TEM represents the water consumption for crop growth, without further drainage considered. Further modeling details can be found in previous studies [*Zhuang et al.*, 2002, 2003].

The well-organized TEM was then parameterized for maize, switchgrass, and *Miscanthus* ecosystems. Most parameters are constant and have been defined in previous studies (e.g., [*McGuire et al.*, 1992; *Zhuang et al.*, 2003]). Some others, either soil-specific or species-specific parameters, were calibrated using observational data with respect to climate, soil conditions, ecosystem C and N pools, and fluxes. The TEM version used here has been well parameterized for maize, switchgrass, and *Miscanthus* and applied to large regions to assess C and water dynamics [*Qin et al.*, 2011, 2013; *Zhuang et al.*, 2013].

30.2.3. Model Application and Regional Analysis

By assuming that maize, switchgrass, and *Miscanthus* will be grown on the currently available maize-producing areas in the conterminous United States, TEM was applied to simulate the ecosystem C, N, and water dynamics separately for three different ecosystems. The model was forced by spatially referenced information on climate, elevation, soil, and vegetation. The grid-by-grid model outputs, including spatially explicit NPP, NCE, and EET, were used to analyze spatial and regional dynamics of biomass, C, and water.

The model input data describing climate, elevation, soil, and vegetation were organized at a 0.25° latitude × 0.25° longitude spatial resolution. Specifically, the driving climate data, including the monthly air temperature, precipitation, and cloudiness, were based on CRU (Climatic Research Unit) [*Mitchell and Jones*, 2005]. Annual atmospheric CO_2 concentrations were derived from the Mauna Loa records (http://www.esrl.noaa.gov/gmd/ccgg/trends/). The elevation data were collected from the Shuttle Radar Topography Mission (SRTM) [*Farr et al.*, 2007]. Soil data indicating soil texture of sand, silt, and clay content were based on the Food and Agriculture Organization/Civil Service Reform Committee (FAO/CSRC) digitization of the FAO/UNESCO soil map of the world (1971). Vegetation map describing national crop distribution were extracted from a global crop harvest area database [*Monfreda et al.*, 2008]. These time series data, mostly climate data, were collected from 1900 to 2000, with a time step of one month.

Model simulations were run separately for each crop over the United States at a monthly time step. For each simulation, TEM was first run to equilibrium using the data of 1900, to determine the model initial conditions. Then the model was spun-up for 150 years by repeatedly using the first 50 years' data. The transient simulations were finally run through the 1900–2000 period, and grid-level model outputs of the 1990s were collected for regional analysis. For each ecosystem (i.e., maize, switchgrass, and *Miscanthus*), biomass production (i.e., NPP), C balance (i.e., NCE), and water loss (i.e., EET) were estimated in the model simulations. Water use efficiency (WUE), generally defined as biomass production or yield gain per unit of water consumption, was also used to measure the efficacy of economic gain (e.g., NPP) or ecological gain (e.g., NCE) relative to an environmental cost of water loss [*Ito and Inatomi*, 2012; *Niu et al.*, 2011; *VanLoocke et al.*, 2012]. In this study, biomass WUE ($\mathrm{WUE_B}$) and carbon WUE ($\mathrm{WUE_C}$) were defined in terms of biomass production [equation (30.4)] and C balance [equation (30.5)] at the cost of unit water loss, respectively:

$$\mathrm{WUE_B} = \mathrm{NPP} / \mathrm{EET}, \tag{30.4}$$

$$WUE_C = NCE / EET. \quad (30.5)$$

Spatial analyses were conducted to estimate spatial distribution and regional average of C and water dynamics, based on spatially explicit TEM simulations. The decadal averages of the 1990s were presented to show biomass production, C exchange, and water use efficiency.

30.3. RESULTS

30.3.1. Ecosystem Productivity

Ecosystem production, in terms of NPP and NCE, varies among different ecosystems and also differs over space due to spatial heterogeneity of climate, soil, and vegetation conditions. As reported previously, most biomass production concentrates in the intensive cropping areas in the Midwest [*Qin et al.*, 2012]. The grid-level NPP statistics (not area weighted) show that (Figures 30.2a–30.2c) maize has a relatively small spatial variation, with 500–900 g C/m^{-2} of NPP at most grids. *Miscanthus*, however, shows widely distributed NPP with most grids ranging from 1100 to 1900 g C/m^{-2}. From the perspective of national average, *Miscanthus* produces twice as much NPP as maize or switchgrass could (Table 30.1).

In TEM, NCE accounts for the net C balance at the ecosystem scale, and the flux is highly dependent on the spatially explicit environmental conditions such as soil and climate. For maize, most of the intensive cropping areas in the Midwest (except the Illinois area) act as net C sources (Figure 30.3a). Swichgrass and *Miscanthus*, however, have vast areas showing positive

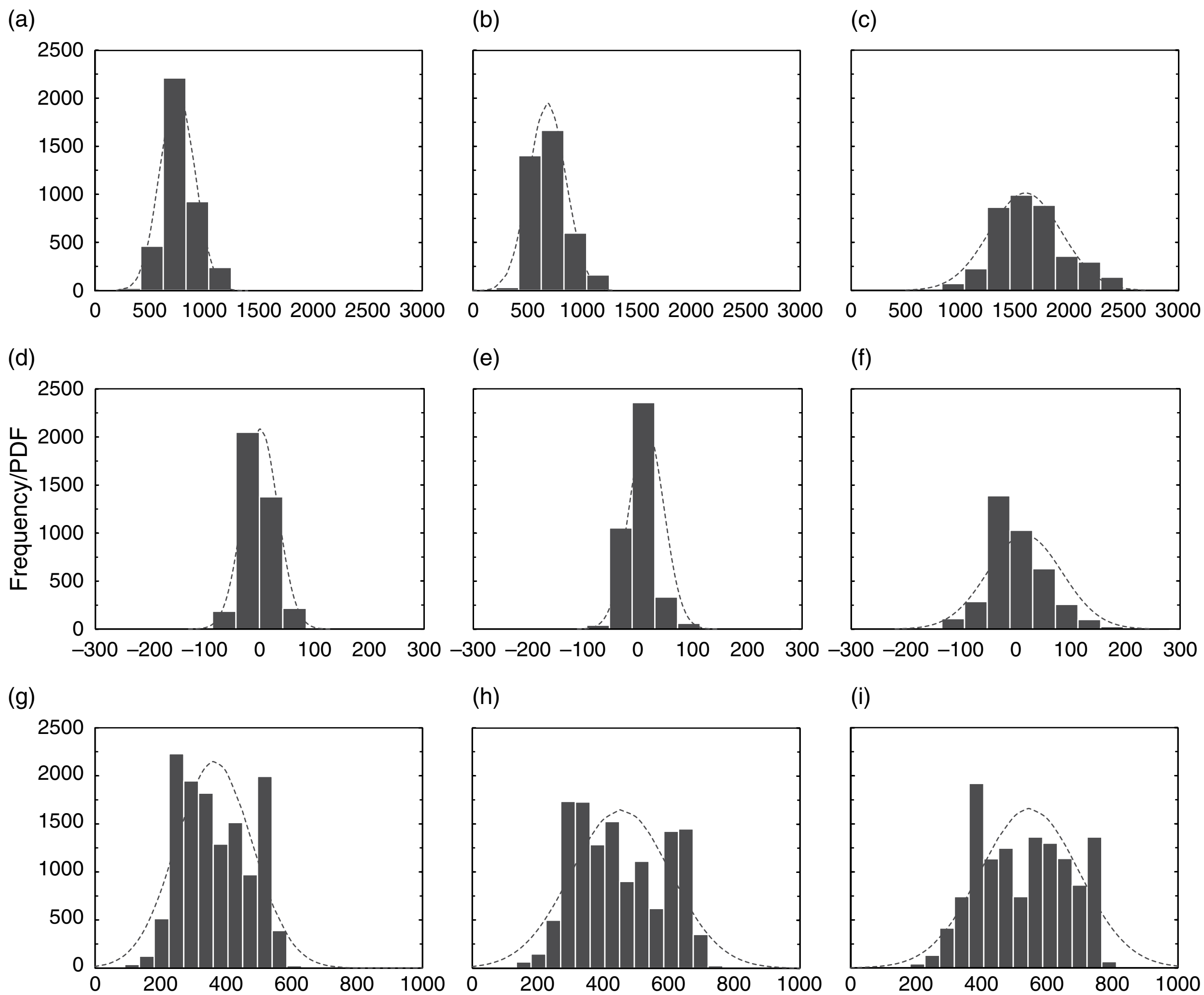

Figure 30.2 Spatial variations of the estimated NPP, NCE, and EET. Grid-level estimates were made for NPP (g C/m^{-2} yr^{-1}) of (a) maize, (b) switchgrass, and (c) *Miscanthus*; NCE (g C/m^{-2} yr^{-1}) of (d) maize, (e) switchgrass, and (f) *Miscanthus*; and EET (mm) of (g) maize, (h) switchgrass, and (i) *Miscanthus*. The NPP, NCE, and EET are presented with bars showing frequency and dashed lines indicating Gaussian distribution. Actual vegetation area of grid is not considered.

Table 30.1 Estimated national average NPP, NCE, and EET

Crop	NPP (g C/m^{-2})	NCE (g C/m^{-2})	EET (mm)
Maize	713 (66)	−1.9 (0.3)	347 (42)
Switchgrass	622 (49)	7.1 (1.0)	440 (45)
Miscanthus	1513 (122)	11.0 (1.9)	523 (51)

Note: Net primary production (NPP), net carbon exchange (NCE), and evapotranspiration (EET) are reported as corresponding decadal averages (1990s) with temporal standard deviations in parentheses. NPP details can also be found in *Qin et al*. [2012].

NCE and therefore potentially mitigate C emissions (Figures 30.3b and 30.3c). Spatially, about 90% of the cropping grids have an NCE (not area weighted) ranging from −50 to 50 g C/m^{-2} in maize and switchgrass ecosystems. Even though switchgrass has a positive mean NCE and maize has a negative value, they share similar spatial variation with a standard deviation (SD) of about 30 g C/m^{-2} (Figures 30.2d and 30.2e). *Miscanthus*, however, has a more spatially heterogeneous NCE distribution, with about 60% grids ranging from −50 to 50 g C/m^{-2} and 86% ranging from −100 to 100 g C/m^{-2} (Figure 30.2f). Considering actual cropping area, the maize ecosystem produces a national average NCE of −1.9 g C/m^{-2}. The switchgrass and *Miscanthus* ecosystems produce 9 and 12.9 g C/m^{-2} more NCE than maize, respectively, both acting as C sinks at national scales (Table 30.1).

The model results suggest that crop switching from maize to switchgrass may cause a net decrease of NPP of 91 g C/m^{-2} nationally but, meanwhile, may create a national C sink. If switched to *Miscanthus*, the ecosystem would increase both biomass production and potential C mitigation.

30.3.2. Evapotranspiration at Ecosystem Scales

Cellulosic crop ecosystems, especially a *Miscanthus* ecosystem, show a significantly higher evapotranspiration than a maize ecosystem, as simulated from TEM. As shown in our previous report [*Zhuang et al.*, 2013], EET distributes mainly along the dominant maize-producing areas in the Midwest, with especially high annual EET in the states of Illinois and Indiana. Compared with a maize ecosystem, switchgrass has an overall higher EET and *Miscanthus* has the highest EET among all. Annual EET varies dramatically over space. It was estimated that, across the majority of cropping areas, the actual water loss through EET is 200–550 mm in maize ecosystems and increases to 250–600 mm in switchgrass and 300–800 in *Miscanthus* ecosystems [*Zhuang et al.*, 2013]. Statistically, the maize ecosystem has the lowest mean EET, as well as the smallest spatial EET variation among all three crop systems (Figure 30.2g). Switchgrass (Figure 30.2h) and *Miscanthus* (Figure 30.2i), show respective increases of one quarter and one half on the basis of maize in terms of both mean and variation.

According to estimates based on maize harvested areas, the national average EET of switchgrass and *Miscanthus* is 27% and 51% higher than that of maize, respectively (Table 30.1). If, as hypothesized here, crop switching from maize to bioenergy crops such as switchgrass or *Miscanthus* occurs, the annual EET will increase in most areas. Due to land cover change from maize to switchgrass, the EET increases about 90 mm on average, with 60–120 mm increase in most places. If crop is changed to *Miscanthus*, the EET of most locations will increase 140–210 mm, with an annual average increase of 176 mm (Table 30.1). Similar results have also been reported, mostly for the Midwest of the United States. By applying a multilayer canopy model, *Le et al*. [2011] estimated evapotranspiration under climate condition of 2005. It was reported that switchgrass and *Miscanthus* have, respectively, 118 and 208 mm higher total EET than maize. *Vanloocke et al*. [2012] simulated 30 year (1973–2002) hydrology using an ecosystem model and estimated that switchgrass EET is 25–150 mm higher and *Miscanthus* is 50–200 mm higher than maize EET. These results are comparable, and the differences are partly caused by input data, including climate and soil data, model structure, simulation year, and the study regions. It was believed that the EET differences between maize and these bioenergy crops are mostly resulted from the density and architecture of aboveground foliage [*Le et al.*, 2011].

30.3.3. Water Use Efficiency

The WUE_B and WUE_C were determined, respectively, as NPP and NCE produced at cost of each unit of water loss through evapotranspiration. Generally, the spatial distribution of WUE_B shows that the switchgrass ecosystem has lower efficiency than maize and *Miscanthus* ecosystems (Figures 30.4a–30.4c). *Miscanthus*, in particular, has the highest WUE in most Midwest areas (Figure 30.4c). This is understandable considering that switchgrass produces the lowest NPP but with higher EET in comparison with maize. *Miscanthus* consumes even more water than switchgrass, but its biomass production more than doubles that of maize or switchgrass, and thus owns much high WUE_B. Unlike NPP and EET, the pattern of WUE_B spatial distribution is similar among different ecosystems (Figures 30.5a–30.5c). Averaged over the whole cropping area, the national WUE_B of maize, switchgrass, and

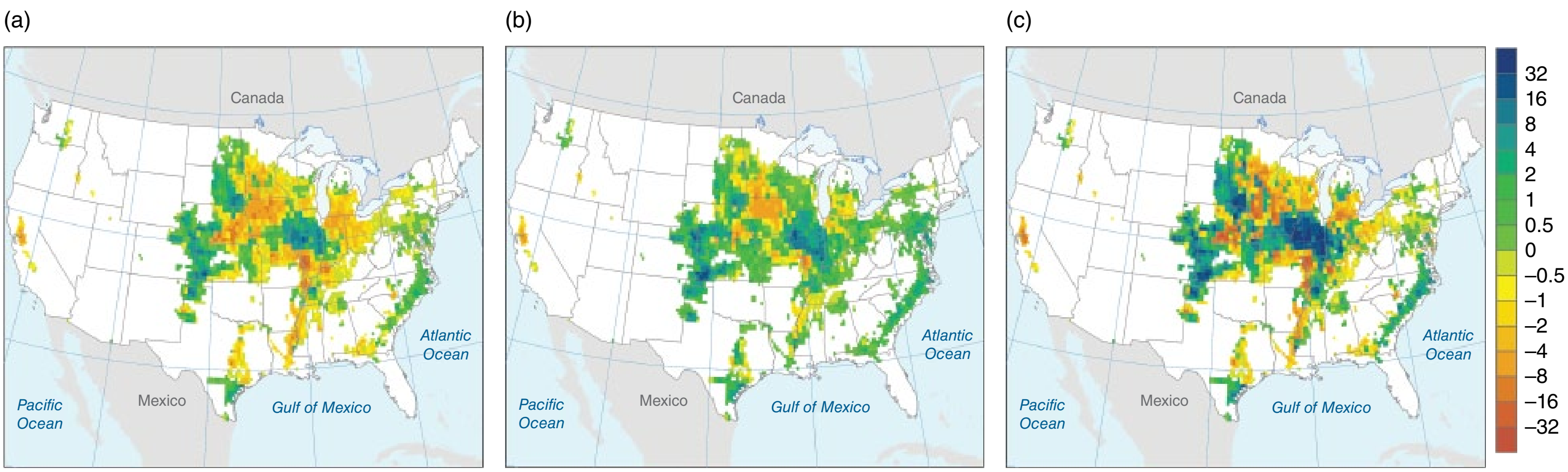

Figure 30.3 Estimated spatial NCE over the maize-producing areas in the United States. Spatial estimates were made for NCE (g C/m^{-2} yr^{-1}) of (a) maize, (b) switchgrass, and (c) *Miscanthus*. Grid-level NCE values are area weighted. Note: Spatial estimates for NPP [*Qin et al.*, 2012] and EET [*Zhuang et al.*, 2013] were reported previously.

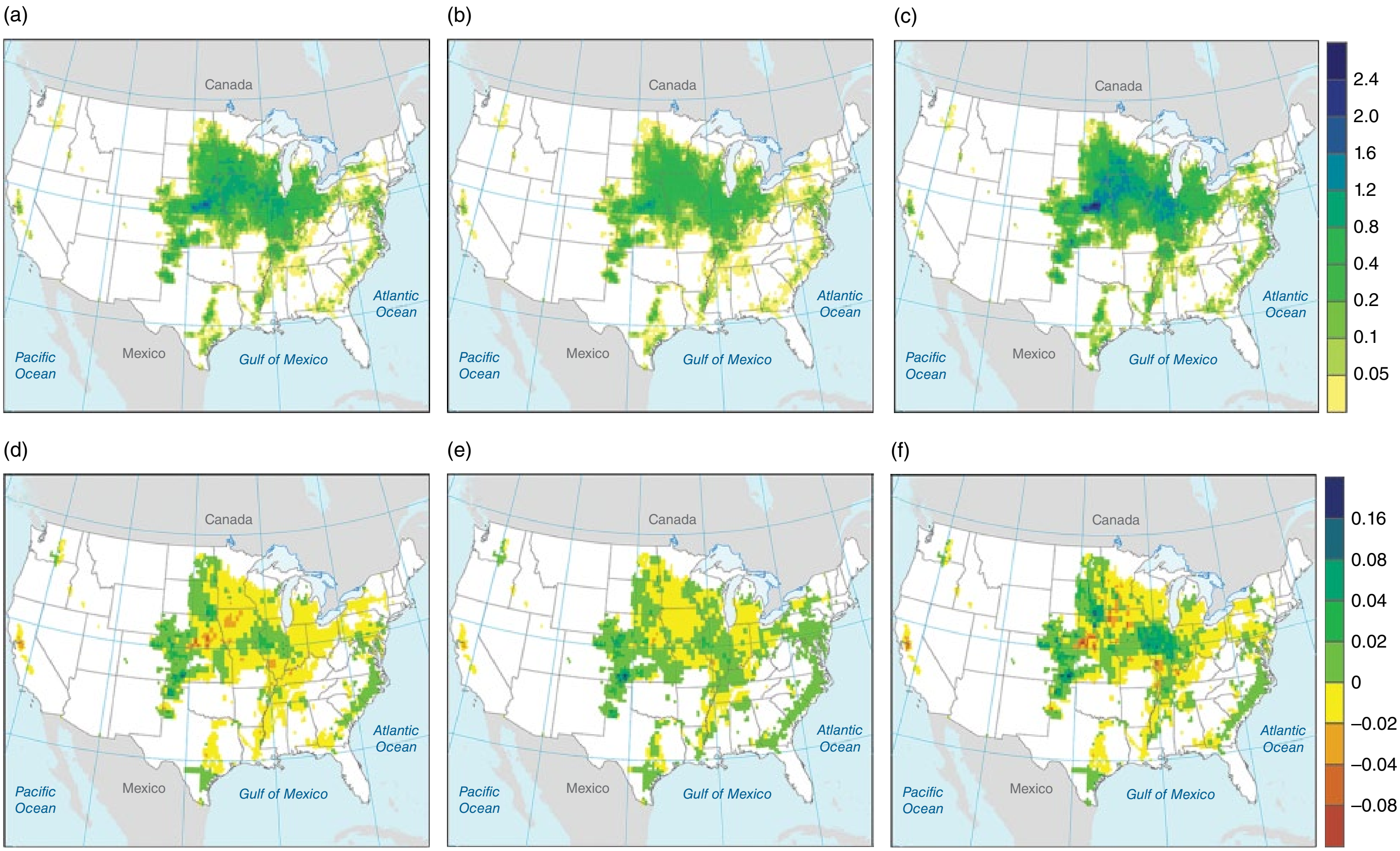

Figure 30.4 Estimated spatial WUE of NPP and NCE over the maize-producing areas in the United States. Spatial estimates were made for WUE of NPP (kg C/m^{-3}) of (a) maize, (b) switchgrass, and (c) *Miscanthus*, and WUE of NCE (kg C/m^{-3}) of (d) maize, (e) switchgrass, and (f) *Miscanthus*. Grid-level values are area weighted.

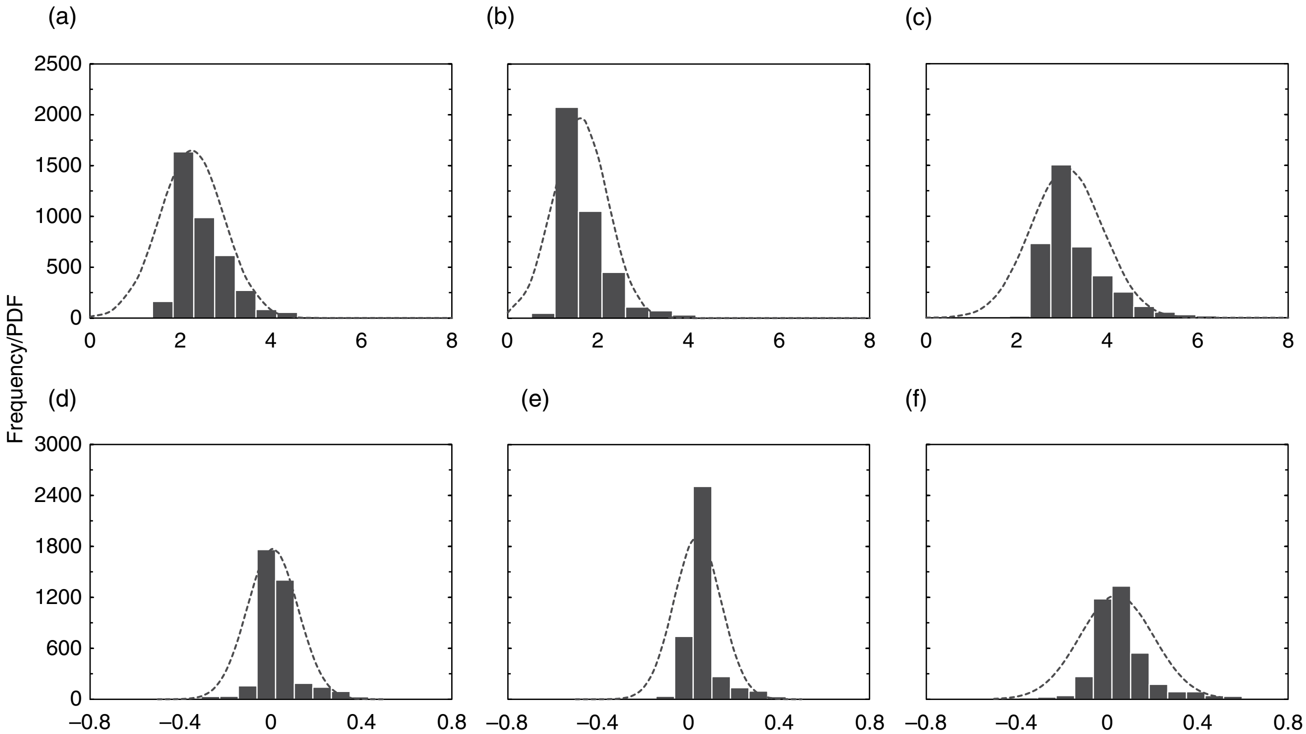

Figure 30.5 Spatial variations of estimated WUE. Grid-level estimates were made for WUE of NPP (kg C/m^{-3}) of (a) maize, (b) switchgrass, and (c) *Miscanthus*, and WUE of NCE (kg C/m^{-3}) of (d) maize, (e) switchgrass, and (f) *Miscanthus*. The WUE of NPP and NCE are presented with bars showing frequency and dashed lines indicating Gaussian distribution. Actual vegetation area of grid is not considered.

Miscanthus are 2.3, 1.6, and 3.1 kg C/m^{-3}, respectively (Table 30.2). That is, with each unit of water loss, *Miscanthus* could produce 35% more NPP than maize and 94% more than switchgrass.

The WUE_C spatial distribution shows the size of NCE flux relative to EET and the net impact of C mitigation (Figures 30.4d–30.4f). For NCE, the negative WUE_C indicates a net C source and the positive one indicates a C sink. Apparently, the maize ecosystem has more areas acting as net C sources and the WUE_C is 0 ± 0.02 kg C/m^{-3} at most sites (Figure 30.4d). Statistics shows that over 80% of grids lie between −0.05 and 0.05 kg C/m^{-3} of WUE_C (Figure 30.5d). For switchgrass, most of the cropping area shows a small positive WUE_C (Figure 30.4e), with about 65% of grids in the range of 0–0.05 kg C/m^{-3} (Figure 30.5e). A *Miscanthus* ecosystem has much higher spatial variations than maize and switchgrass ecosystems, with about 90% of grids ranging between −0.2 and 0.3 kg C/m^{-3} (Figure 30.5f). Overall, the maize ecosystem acts as a net C source with smallest WUE_C at national scales, and cellulosic ecosystems act as a net C sink with similar WUE_C. For each cubic meter of water loss, maize produces 5.0 kg C of C emissions. Switchgrass and *Miscanthus* mitigate 18.4 and 22.5 kg C of C emissions, respectively (Table 30.2).

Table 30.2 National average water use efficiency

	Water Use Efficiency	
Crop	WUE_B (kg C m^{-3})*	WUE_C (g C m^{-3})†
Maize	2.3 (0.7)	−5.0 (0.7)
Switchgrass	1.6 (0.6)	18.4 (2.0)
Miscanthus	3.1 (0.8)	22.5 (3.4)

Note: Water use efficiency of biomass* and carbon exchange† were calculated as in equations (30.4) and (30.5), respectively. Results are reported as decadal averages (1990s) with temporal standard deviations in parentheses.

30.4. DISCUSSION

30.4.1. Input Use Efficiency as a Measure of Resource Allocation

Climate conditions, soil fertility, land availability, and water availability are several dominant environmental factors determining crop growth and biomass production. Land and water, in particular, are two major resources for producing biomass feedstock. Among the three energy crops, each will exclude others from using a certain amount of water at a given region. The goal of this study is to evaluate the ecosystem production of these crops under the same environmental conditions, but with different cropping systems. As estimated here and reported elsewhere [*Heaton et al.*, 2008; *Qin et al.*, 2012], cellulosic crops (particularly *Miscanthus*) are capable of accumulating a considerable amount of C (e.g., NPP) and using soil nutrients efficiently (e.g., nitrogen), at a given land area. They have higher land use efficiency (LUE) than many food-based crops (e.g., maize) in terms of biomass production per land area. This is mostly because cellulosic crops have a high photosynthetic productivity due to important characteristics such as high efficiency of solar radiation interception and conversion [*Heaton et al.*, 2008], large leaf area, and long canopy duration [*Dohleman and Long*, 2009; *Heaton et al.*, 2004]. Switchgrass and *Miscanthus* could also produce positive NCE, making great contributions to C mitigation (Table 30.1). Compared with annual plants (e.g., maize), these perennial plants could survive multiple years with less soil disturbance due to agricultural management such as tillage and rotation [*Heaton et al.*, 2004]. Also, the cellulosic ecosystems can sequester a large amount of C in belowground biomass and keep a relatively high level of soil carbon [*Kahle et al.*, 2001; *Lee et al.*, 2007].

It is possible that maize may outweigh cellulosic crops in terms of biomass-based WUE, due to its lower water loss during growth. Switchgrass is indeed less efficient than maize due to its lower biomass productivity and higher water use. *Miscanthus*, however, is still more productive in biomass production when using the same amount of water (Table 30.2). It was reported that, per cubic meter of water depletion, about 1.1–2.7 kg maize yield was produced globally [*Zwart and Bastiaanssen*, 2004]. That is about 1.0–2.4 kg C/m^{-3} of WUE_B. The results for the United States in this study fall in the upper end of this range, and comparable with other site [*Hickman et al.*, 2010] or regional estimates [*VanLoocke et al.*, 2012]. A similar estimation in the Midwest also found that *Miscanthus* has higher and switchgrass has lower WUE_B than maize [*VanLoocke et al.*, 2012]. It suggests that productive *Miscanthus* compensates its high LUE for water loss and still results in a relatively high WUE_B. Switchgrass, however, is highly water consuming but with no comparable LUE or biomass productivity. In terms of WUE_C, the model experiments here and elsewhere [*VanLoocke et al.*, 2012] suggest that switchgrass and *Miscanthus* could positively affect ecosystem C sequestration while maize has a negative impact. From the perspective of resource use (mainly land and water), *Miscanthus* rather than switchgrass could be an efficient substitute to maize as biomass feedstock resource.

Other resources besides land and water should also be factored into the consideration of crop switch. For example, fertilizer application and nutrient uptake are key factors determining crop nutrient use efficiency (NUE). It was reported that cellulosic crops may require less fertilization than maize due to their high NUE [*Fargione et al.*, 2010; *Lewandowski et al.*, 2003]. This may further benefit greenhouse gas mitigation since nitrogen fertilizer contributes significantly to ecosystem nitrous oxide emissions [*Hoben et al.*, 2011]. It should also be noted that input use efficiency assesses the biomass or C productivity relative to resource input but does not necessarily consider the economic, temporal, or spatial availability of these resources. Especially in the study, water input only accounted for precipitation and did not consider possible irrigation and other agricultural practices (e.g., tillage and rotation) that may affect water available for crop growth. Further analyses regarding issues of water availability still await future study.

30.4.2. Limitations and Future Needs

Unlike crop models that focus on crop yield estimation, ecosystem models are often used to estimate biogeochemical cycles in natural or agricultural ecosystems. Even with simulated C dynamics and additional algorithms describing C allocation and crop yield formation, ecosystem models, such as TEM, are still lacking detailed information and processes on agricultural management, more often lacking supporting data, which may further impact the accuracy of biomass prediction [*Qin et al.*, 2012]. More data of agricultural practices, such as irrigation, rotation, tillage, fertilizer application, and timing of planting, will improve ecosystem model predictability. Still, caution should be used when interpreting spatial heterogeneity of these practices and corresponding spatial data [*Davis et al.*, 2012; *VanLoocke et al.*, 2010].

Miscanthus would not be grown on croplands for biofuel simply because of its high LUE and WUE. Many other factors should also be included in a life-cycle assessment for certain biofuels [*Davis et al.*, 2009]. Issues such as food security, economic viability, and ethical concerns could all affect decision making [*Fargione et al.*, 2010; *Pimentel et al.*, 2010; *Tilman et al.*, 2009]. From the environmental perspective, many issues concerning biofuel development and land use introduce large uncertainties into regional estimations of large-scale bioenergy expansion. Growing bioenergy crops, especially cellulosic crops, instead of conventional food crops, may have fundamental impacts on ambient climate (e.g., greenhouse gas, air temperature, moisture) [*Bessou et al.*, 2011; *Hallgren et al.*, 2013], soil quality (e.g., soil carbon, soil acidity) [*Cayuela et al.*, 2010; *Clifton-Brown et al.*, 2007], water quality (e.g., N and P concentration), as well as water quantity [*Behnke et al.*, 2012; *Skinner et al.*, 2012]. These impacts are important but not well studied for the newly established ecosystems, such as switchgrass and

Miscanthus. More evidence from field observations is required to improve ecosystem modeling and large-scale model extrapolation.

In our study, we only considered maize cropland for biofuel cropping. However, other types of land could also serve as potential biofuel land sources. For example, conservation reserve program land could be properly cultivated to produce biomass [*Lee et al.*, 2013]. Marginal lands, including most abandoned or degraded cropland and grassland where most traditional food crops may not survive due to poor soil or climate conditions, could be used to grow cellulosic crops with high environmental stress resistance [*Gelfand et al.*, 2013; *Varvel et al.*, 2008]. Switchgrass, under this circumstance, could be much more competitive than maize with higher LUE. But still, besides biomass production, other environmental issues including water availability, nutrient sustainability, and those understudied problems for cropland should be further investigated to uncover the potential consequences of growing cellulosic crops (e.g., switchgrass and *Miscanthus*) on marginal lands.

30.5. SUMMARY

To assess WUE of bioenergy crops (i.e., maize, switchgrass, and *Miscanthus*) grown on cropland, an ecosystem model was used to estimate regional ecosystem productivity and evapotranspiration over the conterminous United States. Compared with maize, switchgrass has relatively lower biomass productivity while *Miscanthus* has much higher productivity. Nationally, both cellulosic crops have higher net carbon exchange than maize, acting as net C sinks. Further analyses suggest that, in terms of biomass production at the cost of unit water loss, the productive *Miscanthus* compensates its high land use efficiency for water loss and results in the highest water use efficiency among three bioenergy crops. Switchgrass, however, is highly water-consuming but with no comparable biomass productivity. Its water use efficiency is the lowest among the three crops. At given water loss level, switchgrass and *Miscanthus* ecosystems sequester a similar amount of carbon, while the maize ecosystem releases carbon. More evidence from field observations is required to improve ecosystem modeling and large-scale extrapolation analysis of other environmental impacts. Further analyses on using other land sources (e.g., marginal lands) should also be conducted for future biofuel development.

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