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Biofuel, land and water: maize, switchgrass or *Miscanthus*?

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Abstract
The productive cellulosic crops switchgrass and *Miscanthus* are considered as viable biofuel sources. To meet the 2022 national biofuel target mandate, actions must be taken, e.g., maize cultivation must be intensified and expanded, and other biofuel crops (switchgrass and *Miscanthus*) must be cultivated. This raises questions on the use efficiencies of land and water; to date, the demand on these resources to meet the national biofuel target has rarely been analyzed. Here, we present a data-model assimilation analysis, assuming that maize, switchgrass and *Miscanthus* will be grown on currently available croplands in the US. Model simulations suggest that maize can produce 3.0–5.4 kiloliters (kl) of ethanol for every hectare of land, depending on the feedstock to ethanol conversion efficiency; *Miscanthus* has more than twice the biofuel production capacity relative to maize, and switchgrass is the least productive of the three potential sources of ethanol. To meet the biofuel target, about 26.5 million hectares of land and over 90 km^3 of water (of evapotranspiration) are needed if maize grain alone is used. If *Miscanthus* was substituted for maize, the process would save half of the land and one third of the water. With more advanced biofuel conversion technology for *Miscanthus*, only nine million hectares of land and 45 km^3 of water would probably meet the national target. *Miscanthus* could be a good alternative biofuel crop to maize due to its significantly lower demand for land and water on a per unit of ethanol basis.

Keywords: bioenergy, ecosystem modeling, land use efficiency, water use efficiency

S Online supplementary data available from stacks.iop.org/ERL/8/015020/mmedia

1. Introduction

Biofuels are widely considered to be a major renewable energy source that has the advantage of mitigating climate warming (Tilman *et al* 2009, Fargione *et al* 2010, Beringer *et al* 2011). Over 40 billion liters (l) (10.6 billion gallons) of fuel ethanol have been made each year in the US since 2009, reaching 52.6 billion liters in 2011. Ethanol plants more than tripled and ethanol production capacity has continually increased during the last decade (RFA 2012). Per government mandate, a total annual production of 136 billion liters renewable fuels, including 79 billion liters of cellulosic biofuels, will be produced by 2022 in the US (USA 2007).

In the US, maize is traditionally considered to be a food crop, but a considerable portion of grain produced since the late 2000s has been devoted to first-generation ethanol production (USDA 2010). However current maize grain yield is not able to support an increasing biofuel feedstock demand without jeopardizing food security (Davis *et al* 2012, Fargione *et al* 2010). The 2022 biofuel goal will unavoidably require agricultural intensification and expansion

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if food crops are to be the major source of feedstock. The lignocellulosic biomass of switchgrass (*Panicum virgatum* L.) and *Miscanthus* (e.g., *Miscanthus giganteus*) has been perceived as alternatives to traditional feedstock to produce second-generation biofuel (Heaton *et al* 2008, Fargione *et al* 2010, Tulbure *et al* 2012a). This is particularly true in temperate regions due to their higher biomass productivity and can potentially be grown on crop-producing area due to their high adaptability to different soil and climate environments (Heaton *et al* 2004, Fargione *et al* 2010, Davis *et al* 2012).

It is well accepted that issues such as biomass production, land and water use in the bioenergy ecosystems are among many that need to be studied regarding energy crop production (Thomas *et al* 2012). There is evidence from field studies indicating bioenergy crops generally have higher land and water use efficiencies than food crops (Clifton-Brown and Lewandowski 2000, McIsaac *et al* 2010, Beale *et al* 1999, Suyker and Verma 2010, Hickman *et al* 2010). However, the large-scale demand of land and water to grow these biofuel crops has rarely been assessed using physiologically based ecosystem models (Richter *et al* 2008, Le *et al* 2011, VanLoocke *et al* 2012).

Here we used a process-based biogeochemical model, the terrestrial ecosystem model (TEM) (Zhuang *et al* 2003, Qin *et al* 2012), to estimate the demand of land and water growing different biofuel crops so as to provide sufficient feedstocks to meet the 2022 US national biofuel target of 79 billion liters ethanol. In the estimates, the conventional maize, switchgrass and *Miscanthus* are assumed to be grown on current maize-producing areas to produce biomass feedstocks. Our study focus is on analyzing the demand of land and water to meet the mandate biofuel target, rather than the environmental benefits and consequences of growing these potential biofuel crops (e.g., Searchinger *et al* 2008; Melillo *et al* 2009 and Fargione *et al* 2010).

2. Methods

2.1. 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 (Raich *et al* 1991, McGuire *et al* 1992). Gross primary production (GPP) is the core algorithm, describing the rate at which the plant produces useful chemical energy. Net primary production (NPP) is the difference between GPP and plant respiration. NPP is mostly referred to as the net biomass production of an ecosystem, in terms of carbon fixation rate (Raich *et al* 1991, McGuire *et al* 1992). In TEM, GPP is modeled as a function of the maximum rate of C assimilation and environmental variables, including irradiance of photosynthetically active radiation, atmospheric CO_2 concentration, relative canopy conductance, air temperature, moisture, and nitrogen (N) availability (Chen *et al* 2011). Improved soil thermal and hydrological dynamics were incorporated into the version of TEM used in this study (Zhuang *et al* 2002, 2003). The model has been extensively used to evaluate C and N dynamics, and simulate hydrology in terrestrial ecosystems (e.g., Qin *et al* 2011, Qin *et al* 2012, Taheripour *et al* 2012 and Zhuang *et al* 2010).

In TEM, the hydrological cycle consists of processes of precipitation (rainfall and snowfall), sublimation, evaporation, interception, throughfall, percolation, transpiration, runoff and drainage (Zhuang *et al* 2002). Potential evapotranspiration is modeled according to the Jensen–Haise formulation (Jensen and Haise 1963) and depends on air temperature and radiation (Zhuang *et al* 2002). Actual evapotranspiration (EET) in the model is estimated based on the calculations of evaporation, sublimation and transpiration (Zhuang *et al* 2002). More details on hydrological modeling can be found in previous studies (Zhuang *et al* 2002, 2004).

To analyze the productivity of feedstocks and biofuels, we estimated biomass and biofuel production in terms of harvestable biomass (HBIO) and bioethanol yield. HBIO is the proportion of NPP that can be harvested as biomass feedstock for biofuel production, and is generally modeled as:

$$\mathrm{HBIO} = \frac{\mathrm{NPP} \times B_{\mathrm{abv}} \times HI \times (1 - B_{\mathrm{los}})}{C_{\mathrm{dm}}} \qquad (1)$$

where B_{abv} is the proportion of aboveground biomass for a certain crop, C is the carbon content in the dry matter (DM) ($C_{\mathrm{dm}} = 0.45$), B_{los} is biomass loss or return and HI refers to harvest index, measuring the proportion of total aboveground biomass allocated to economic yield of the crop (table S1 available at stacks.iop.org/ERL/8/015020/mmedia). Additionally, biomass harvest is expressed as a fraction of ecosystem biomass production, regardless of environmental or economic feasibility, unless otherwise stated; maize can be harvested as either grain or stover for the purpose of bioenergy production. Bioethanol produced from biomass varies among the different feedstocks due to different biomass-to-biofuel conversion efficiencies C_{bio} (table S1 available at stacks.iop.org/ERL/8/015020/mmedia). Conversion technology for corn grain is well established; the current and potential achievable conversion efficiencies are quite close. However, biofuel yield from cellulosic biomass can be amplified from a current low level to a much higher level when potential technology advances (table S1 available at stacks.iop.org/ERL/8/015020/mmedia) (Lynd *et al* 2008, Fargione *et al* 2010). Both current and potential biofuel production were estimated according to biomass-to-biofuel conversion efficiencies under currently available and potentially advanced technologies, respectively.

In TEM, most parameters are constant and have already been defined in previous studies (e.g., McGuire *et al* 1992 and Zhuang *et al* 2003). Some others, especially those vegetation-specific parameters, have to be calibrated. In this study, observational data used for calibration including temperature, precipitation and cloudiness data for the 1990s, as well as crop ecosystem data including C and N fluxes and pools. For each calibration site, TEM was run numerous times to achieve model equilibrium. The simulated GPP and NPP were compared against the observed values to optimize the TEM parameters (see details in Qin *et al* 2011 and Qin *et al* 2012). The optimized parameters were then used in regional simulations (table S2 available at stacks.iop.org/ERL/8/015020/mmedia).

2.2. Regional application and analysis

Based on spatially referenced information on climate, elevation, soil, and vegetation, TEM was applied to the maize-producing areas in the conterminous US to estimate crop biomass production, biofuel yield, as well as water balance. By assuming crops are grown on the existing maize-producing areas, TEM simulated C, N and water dynamics for maize, switchgrass and *Miscanthus* at a 25 km latitude $\times$ 25 km longitude resolution. Crop biomass productivity, HBIO, and biofuel productivity were calculated based on NPP estimates. Finally, regional analyses about biomass and biofuel yield, water balance, and water use efficiency were conducted based on grid-level results.

For each model simulation, we first ran TEM over the whole US at a grid cell level at a monthly time step from 1990 to 1999. Each grid cell in TEM was assigned a certain crop ecosystem type (i.e., maize, switchgrass and *Miscanthus*) according to crop distribution information of current maize (Monfreda *et al* 2008). Grid-level climate, elevation, soil and vegetation data that we used in TEM were organized at a 25 km $\times$ 25 km spatial resolution. Specifically, the driving climate data, including the monthly air temperature, precipitation and cloudiness, were based on CRU (Climatic Research Unit) data (Mitchell and Jones 2005). The elevation data were from the Shuttle Radar Topography Mission (SRTM) (Farr *et al* 2007) and soil texture data 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) (Lu *et al* 2009, Qin *et al* 2012). Cropland distribution information was extracted from a global crop harvest area database (Monfreda *et al* 2008). For this study, a total harvested area of 30.9 Mha maize was estimated for the conterminous US (figure S1(a) available at stacks.iop.org/ERL/8/015020/mmedia). The precipitation shows a significant spatial variability with an annual mean precipitation of 559 mm over the maize-producing areas in the 1990s (figure S1(b) available at stacks.iop.org/ERL/8/015020/mmedia.

Biomass production, biofuel yield and water balance for each crop type in the study area was estimated based on simulations. Water use efficiency (WUE), generally defined as biomass or biofuel production per unit water consumed, was calculated to measure the efficacy of ecological gain (e.g., carbon accumulation) or economic gain (e.g., bioenergy production) relative to the water loss; EET indicates the water consumption for crop growth (VanLoocke *et al* 2012). Land use efficiency (LUE) measures the land used for a certain amount of biomass or biofuel being produced.

Regional results were weighted by the crop harvest area to account for spatial variability in crop distribution and NPP. The averages over the 1990s were presented to show spatial distribution and national total biomass production, biofuel yield and water balance.

3. Results and discussion

We found that to produce 79 billion liters ethanol from maize grain, given currently achievable biomass-to-biofuel conversion efficiencies, about 190 million ton (Mt) conventional grain, 26.5 million hectare (Mha) land, i.e. 85% of all maize-producing areas (Monfreda *et al* 2008) or 20% of total US cropland (USDA 2007), would be required. Accompanying the maize production via photosynthesis, water loss to the atmosphere due to evapotranspiration would be 92 km^3. However, if the maize stover was also used, 4–9 Mha of cropland and therefore 20–32 km^3 of water would be saved. Using cellulosic switchgrass to produce the same amount of ethanol would result in higher biomass demand (280 Mt) due to the low conversion efficiency, and greater amounts of land and water would be needed to produce the same amount of biomass. In contrast, using *Miscanthus* requires only half of the cropland and two-thirds of the water used for maize grain. If advanced biomass-to-biofuel conversion technologies are available in the 2020s, even less land and water resources would be required when using *Miscanthus* as feedstocks. About 9 Mha land and 45 km^3 water would be able to support *Miscanthus*, producing 79 billion liters ethanol; this represents 63% of the land and 89% of the water needed to grow maize grain and stover for the same purpose (figure 1).

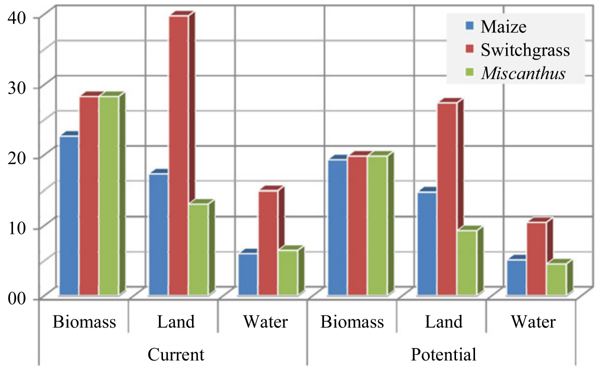

Figure 1. Total biomass, land and water required to achieve the 2022 bioenergy target. Estimates are based on the assumption that 79 billion liters bioethanol would be developed from maize grain and all stover, switchgrass or *Miscanthus* biomass, under current or potential biomass-to-biofuel conversion technologies. Units are 10 Mt for biomass, Mha for land, and 10 km^3 for water loss.

Cellulosic crops, especially *Miscanthus*, transpire more water to the atmosphere than maize (figures 2(d)–(f)). Water loss through evapotranspiration (not area weighted) from maize ecosystem ranges from 200 to 550 mm, while water loss increases to 250–600 mm for switchgrass and 300–800 mm for *Miscanthus*. These estimates are close to an earlier estimate for the Midwest Corn Belt (VanLoocke *et al* 2012). Among three energy crops, *Miscanthus* has the highest harvestable biomass of 21.5 Mg DM ha^{-1} yr^{-1}, more than double the amount of maize or switchgrass (figures 2(a)–(c)). Thus from the perspective of biomass production per unit of water loss, *Miscanthus* has the highest productivity of about 4.4 kg DM m^{-3} water loss. In contrast, switchgrass has the lowest of around 1.9 kg DM m^{-3} on average. Compared with switchgrass, maize's productivity is 50%–100% higher depending on stover harvest.

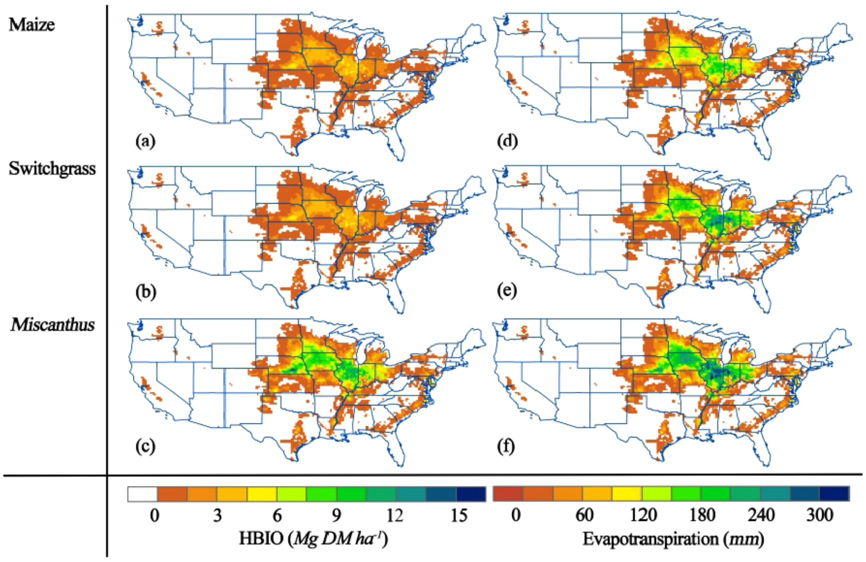

Figure 2. Harvestable biomass (HBIO) and annual evapotranspiration (EET) of bioenergy crops grown on the maize-producing areas over the conterminous US. Estimates were made for mean HBIO of (a) maize, (b) switchgrass and (c) *Miscanthus,* and mean EET for (d) maize, (e) switchgrass and (f) *Miscanthus* over the 1990s. Values are weighted by crop harvest area.

Table 1. Land use efficiency and water use efficiency of biomass and biofuel produced from energy crops grown on maize-producing areas over the conterminous US.

Biomass	Land use efficiency[a]		Water use efficiency	
	CBIO	PBIO	CBIO	PBIO
	(kl E ha^{-1})		(l E m^{-3})	
Maize grain	3.0 (0.3)	3.1 (0.3)		
Maize stover[b]	1.6 (0.2)	2.3 (0.2)		
Maize stover[c]	0.5 (0.1)	0.7 (0.1)		
Maize total[b]	4.6 (0.4)	5.4 (0.4)	1.4 (0.4)	1.6 (0.5)
Maize total[c]	3.5 (0.3)	3.8 (0.3)	1.1 (0.3)	1.2 (0.3)
Switchgrass	2.0 (0.2)	2.9 (0.2)	0.5 (0.2)	0.8 (0.3)
Miscanthus	6.1 (0.5)	8.6 (0.7)	1.2 (0.3)	1.8 (0.4)

[a] E, ethanol; CBIO and PBIO are biofuel produced under current and potential biomass-to-biofuel conversion efficiencies, respectively.
[b] All maize stover is harvested except loss.
[c] 70% of total maize stover is lost or returned to soil for the purpose of soil carbon sustainability, only 30% is counted as biofuel feedstocks (Payne 2010).

Our estimation of ethanol production from biomass indicates that for each hectare of maize-producing cropland *Miscanthus* can produce 6.1 kl ethanol given current conversion technologies, and 8.6 kl ethanol under advanced technologies; switchgrass produces only 2.0 and 2.9 kl ethanol respectively, which is even less than maize grain alone (table 1). Using both grain and stover as feedstocks, maize can produce 3.5–5.4 kl ethanol per hectare, depending on technology and the fraction of stover return (table 1). In general, *Miscanthus* has the highest per hectare ethanol yield across the whole maize-producing region (figures 3(a)–(f)).

Under current biomass-to-biofuel conversion technologies, maize falls in between switchgrass and *Miscanthus* in terms of water use to produce the same amount of biofuel, with an average of 1.1–1.4 l E m^{-3}. Water use for switchgrass and *Miscanthus* are 0.5 and 1.2 l E m^{-3}, respectively (table 1). If advanced technologies were available, *Miscanthus* would be the highest and switchgrass the lowest among three biofuel crops (figures 3(g)–(l)). For each cubic meter of water used, *Miscanthus* could reach a potential biofuel production of 1.8 l, while switchgrass could only produce 0.8 l; maize has the potential to achieve 1.6 l m^{-3} of water if stover were also harvested, or 1.2 l with 70% stover returned to soils for soil conservation purpose (table 1).

Our model experiments indicate that crop switching from maize to *Miscanthus* is much more competitive than crop switching to switchgrass in terms of the use efficiencies of water and land (table 1). Crop switching to *Miscanthus* will save land and water, while switching to switchgrass will require more land and water to produce the same amount of biomass feedstocks.

In our analysis, currently available croplands are assumed to be the only land source for bioenergy crops. Recent studies suggest that marginal lands, including abandoned or degraded cropland, could potentially grow cellulosic crops (Cai *et al* 2011, Gopalakrishnan *et al* 2011, Tulbure *et al* 2012b). Further, our and other studies suggest that switchgrass, compared with maize, may have lower biomass productivity when it is grown on traditional cropland (Heaton *et al* 2008, Sang and Zhu 2011). However, on marginal land where maize may not survive, switchgrass could still serve as potential biofuel crops (Meyer *et al* 2010, Gelfand *et al* 2013). Thus, marginal land use for cellulosic crops should be factored into future land and water economic analyses.

Our spatially explicit ecosystem modeling analysis considers multiple components of the atmosphere, soils and crops in estimating biomass production and water loss from biofuel crops. While available field data are used

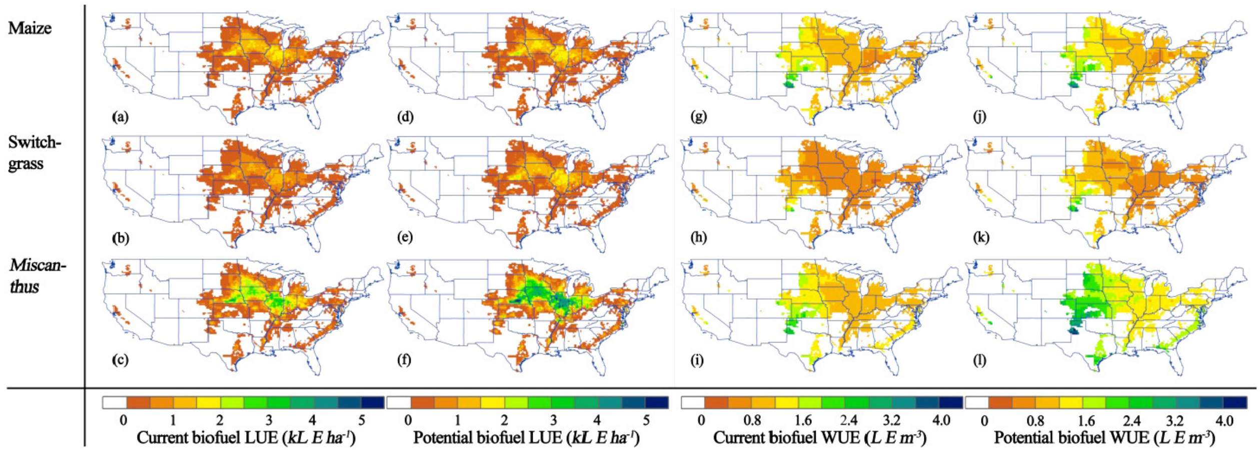

Figure 3. Land use efficiency (LUE) and water use efficiency (WUE) of biofuel produced from different energy crops grown on the maize-producing areas over the conterminous US. Annual mean LUE of current biofuel yield for (a) maize, (b) switchgrass and (c) *Miscanthus*; annual mean LUE of potential biofuel yield for (d) maize, (e) switchgrass and (f) *Miscanthus*; WUE of current biofuel yield for (g) maize, (h) switchgrass and (i) *Miscanthus*; and WUE of potential biofuel yield for (j) maize, (k) switchgrass and (l) *Miscanthus* for the 1990s. LUE values are weighted by crop harvest area.

in a data-model fusion to constrain the uncertainty of biomass production and water loss of these biofuel crops, our model experiments have not considered the effects of fertilization, irrigation, rotation and tillage, which may bias our analysis. Further, our model has not been verified with respect to water use efficiency for these managed biofuel crops. Irrigation experiment data will improve our confidence of estimates of feedstock and evapotranspiration, thereby increasing our confidence of overall estimates of the demand of land and water. In addition, the uncertain conversion technology efficiency of biomass to biofuel may also contribute to the uncertainty. It should also be noted that, the land use assumptions and ecosystem analyses in the study cannot be interpreted as suggestion for large-scale crop switch or agricultural practices. Economic viability, food security, nutritional and ethical concerns, and other potential environmental consequences and benefits such as C sequestration, soil erosion and water quality might also be resulted from switching crops in developing biofuels. We have not analyzed all these aspects in this study.

4. Conclusion

To meet the 2022 national biofuel target by using biomass feedstocks, land availability and water demand are key factors limiting ethanol production. Our model experiments suggest that, among the three potential bioenergy crops, i.e., maize, switchgrass and *Miscanthus*, grown on currently available maize cropland, *Miscanthus* has the highest land use efficiency and water use efficiency, followed by maize, and then the least productive switchgrass. By substituting *Miscanthus* for maize to produce the mandated ethanol, a large amount of land would be saved, and much less water would be needed. Advanced technology will improve biomass-to-biofuel conversion efficiency, consequently the biofuel productivity of crops, especially *Miscanthus*. If cropland has to be used for biofuel production, *Miscanthus* could be an alternative energy crop to maize as the former has a higher use efficiency of land and water.

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