Agricultural and Forest Meteorology 164 (2012) 82–95

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

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

A regional comparison of water use efficiency for miscanthus, switchgrass and maize

Andy VanLoocke[a,d], Tracy E. Twine[b], Marcelo Zeri[d], Carl J. Bernacchi[c,d,*]

[a] Department of Atmospheric Sciences, University of Illinois, 105 South Gregory St., Urbana, IL 61801, USA
[b] Department of Soil, Water, and Climate, University of Minnesota 1991 Upper Buford Circle, 439 Borlaug Hall, St. Paul, MN 55108, USA
[c] USDA-ARS Global Change and Photosynthesis Research Unit, 1201 West Gregory Dr., Urbana, IL 61801, USA
[d] Department of Plant Biology and the Energy Biosciences Institute, University of Illinois at Urbana-Champaign, 1206 West Gregory Drive, Urbana, IL 61801, USA

ARTICLE INFO

Article history:
Received 28 October 2011
Received in revised form 24 March 2012
Accepted 13 May 2012

Keywords:
Evapotranspiration
Land use change
Miscanthus
Ecosystem services
Switchgrass
Maize

ABSTRACT

The production of cellulosic feedstocks for renewable fuels will increase over the coming decades. However, it is uncertain which feedstocks will be best suited for bioenergy production. A key factor dictating feedstock selection for a given region is water use efficiency (WUE), the trade-off between evapotranspiration (ET) and carbon uptake or productivity. Using an ecosystem model, two of the top candidate cellulosic feedstocks, *Miscanthus* × *giganteus* (miscanthus) and *Panicum virgatum* (switchgrass) were compared to *Zea mays* L. (maize), the existing dominant bioenergy feedstock, with 0 and 25% residue removal for the Midwest US. We determined productivity in three ways: harvested yield (HY), net ecosystem productivity (NEP) and net biome productivity (NBP). Evapotranspiration was compared against each of the three productivity metrics, respectively, to yield Harvest Water Use Efficiency (HWUE), Ecosystem Water Use Efficiency (EWUE) and Biome Water Use Efficiency (BWUE). Simulations indicated that, over the study domain, miscanthus had a significantly higher HWUE compared to switchgrass and maize, while maize and switchgrass were similar. When EWUE was compared miscanthus was higher than both maize and switchgrass, which were similar for most of the region. Biome WUE was similar for both of the perennials and higher compared to maize for most of the study domain with the exception of the driest regions where maize showed the highest BWUE. Removing 25% of maize residue slightly increased HWUE and greatly decreased BWUE throughout the domain, however only HWUE changes were statistically significant. These results indicate that the feedstock with the highest WUE varied based on the productivity metric, but BWUE for maize was consistently lower than the perennials.

Published by Elsevier B.V.

1. Introduction

Biomass productivity is often considered the determining factor surrounding the adoption of a bioenergy feedstock in a given area. However, key issues concerning environmental impacts and/or ecosystem derived benefits known as ecosystem services should not be neglected in planning the implementation of these feedstocks (Rowe et al., 2009; Smeets et al., 2009). Environmental impacts and ecosystem services of biofuel production include a range of potential changes to ecosystem properties such as soil/water quality, biodiversity and nutrient leaching (Hill et al., 2006). Many of these changes are important drivers of biogeochemical cycles and can be the result of biological processes such as carbon and/or nitrogen fixation as well as anthropogenic processes such as tillage and nutrient application (Tilman et al., 2006). Ecosystem water use is a key component of the hydrologic cycle and through vegetation is intricately linked to other biogeochemical cycles (Sellers et al., 1997). The primary goal of advanced renewable fuel production, including cellulosic derived energy, is to decrease greenhouse gas emissions by 50% relative to current fossil fuel production (Renewable Fuel Standard 2; RFS2). Given the importance of water availability for crop production (Chaves and Oliveira, 2004; Oliver et al., 2009) and increasing competition for agricultural water resources (Steduto et al., 2007; Suyker and Verma, 2010), this objective can only be met if water resources are available to accommodate the growth of high biomass yielding species in a sustainable manner.

Many countries have governmental mandates requiring the use of second generation bioenergy crops (e.g. EC, 2009; EPA, 2010); however, the feedstocks from which the biomass will be derived remain uncertain. Areas with high agricultural productivity, such as the Midwest US, are well suited for the establishment of C4 perennial grasses. Two species, *Miscanthus* × *giganteus* Greef et Deu ex. Hodkinson et Renvoize (miscanthus; Hodkinson and Renvoize, 2001) and *Panicum virgatum* L. (switchgrass), have been proposed

* Corresponding author at: 193 ERML 1201W. Gregory Drive, Urbana, IL 61801, USA. Tel.: +1 217 333 8048.
E-mail address: bernacch@illinois.edu (C.J. Bernacchi).

0168-1923/$ – see front matter. Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.agrformet.2012.05.016

as candidate feedstocks for this region because of high productivity (Heaton et al., 2004, 2008; Somerville et al., 2010). However, a trade-off often exists between productivity/carbon uptake and water use (Jackson et al., 2005), as has been demonstrated for these two species (Hickman et al., 2010; VanLoocke et al., 2010). Therefore, consideration of the total water resources available to plants and the efficiency of biomass productivity relative to the use of water (i.e., water use efficiency; WUE) should be considered when determining the sustainability of introducing new species on landscapes (Wallace, 2000; Somerville et al., 2010).

The term WUE relates the amount of water used for a given amount of biomass production or carbon gain. An increase in the WUE of an agro-ecosystem reflects a larger opportunity for the ecosystem to provide a service, e.g., carbon accumulation, relative to a perceived environmental cost of this service, e.g., water use. Because productivity and carbon uptake can include different aspects of the carbon cycle, a number of different metrics can be used to calculate WUE. Harvested biomass is often used in agricultural studies to calculate WUE, neglecting all other carbon pools. Perennial species, such as those identified as bioenergy feedstocks, invest a greater amount of biomass below-ground (Anderson-Teixeira et al., 2009; Dohleman et al., 2012; Kahle et al., 2001; Neukirchen et al., 1999); this important ecosystem service is neglected when calculating WUE from harvested material alone. Net ecosystem productivity (NEP) represents the total sum of carbon from the net exchange by an ecosystem but does not include carbon removed at harvest (Chapin et al., 2006). Using NEP in calculating WUE allows for direct comparison of the water use relative to the total carbon removal from the atmosphere in a given year. It is generally assumed that all carbon harvested from an ecosystem will eventually be released into the atmosphere through combustion or respiration. The water use associated with the pool of remaining carbon, termed net biome productivity (NBP), provides an assessment of the WUE of other, non-harvest based, ecosystem services. We use these three productivity metrics to describe WUE for each feedstock to determine: (1) Harvest WUE (HWUE) as the total water used in evapotranspiration (ET) to achieve a given harvested biomass; (2) Ecosystem WUE (EWUE) as the total water used for the total annual NEP; and (3) Biome WUE (BWUE) as the total water used for the total annual NBP.

Water use and carbon uptake for traditional row crops such as maize in the Midwest US are well known under a wide range of environmental and management conditions (e.g. Bernacchi et al., 2005; Hollinger et al., 2005; Kucharik and Twine, 2007; Suyker and Verma, 2009, 2010; West et al., 2010; Zwart and Bastiaanssen, 2004). However, commercial-scale production of perennial grasses in the same region where traditional row crops are planted is lacking. This leaves large uncertainty concerning the potential environmental impacts and services that transitioning to large-scale production will have on water resources (Rowe et al., 2009). While perennial C4 grasses such as miscanthus and switchgrass are shown to be more productive (Dohleman et al., 2009; Heaton et al., 2004, 2008) and to reduce greenhouse gas emissions (Clifton-Brown et al., 2007; Davis et al., 2010, 2012) relative to annual crops, they are also shown to have higher annual ET (Hickman et al., 2010; Le et al., 2011; McIsaac et al., 2010; Rowe et al., 2009; VanLoocke et al., 2010). Without measurements from large-scale production of perennial grasses for bioenergy, the only manner to assess WUE is through the use of ecosystem models.

The goal of this study is to compare total water use, productivity, and the three WUE metrics mentioned above for miscanthus, switchgrass and maize over the Midwest US. We predict that (1) compared to maize and switchgrass, miscanthus will use more water throughout much of the Midwest US but the water use will be offset by even higher biomass yielding higher HWUE, (2) relative to maize, the higher water use associated with switchgrass will not be offset by higher harvested biomass and will yield substantially lower HWUE, and (3) higher total carbon uptake and higher belowground biomass components associated with perennial grasses will yield a higher EWUE and BWUE compared with maize. Since maize crop residues are also considered a viable source of cellulosic feedstocks (Sheehan et al., 2003), we also simulate the impact of corn residue removal on the various WUE metrics. We predict (4) that corn residue removal will increase HWUE for maize but this will be offset by large decreases in BWUE. We test our predictions using the Integrated Biosphere Simulator – Agricultural version (Agro-IBIS; Kucharik and Brye, 2003) parameterized and validated against a number of datasets collected on each of the three species.

2. Methods

2.1. Model description

Agro-IBIS is the agricultural version of IBIS (Foley et al., 1996; Kucharik et al., 2000) that was developed to simulate the biogeophysical and anthropogenic processes occurring in cropped as well as natural ecosystems. A biophysically based approach is used to simulate both C3 and C4 photosynthetic pathways and leaf physiology to predict carbon and water exchange (Collatz et al., 1991; Farquhar et al., 1980) on an hourly time step. On the same time step, leaf processes are scaled to the canopy using methods based on the land-surface transfer scheme (Thompson and Pollard, 1995a,b). Carbon allocation and developmental stages are based on temperature thresholds and the accumulation of growing degree days and are dynamic throughout the growing season. Agro-IBIS calculates belowground daily fluxes and pools of nitrogen and carbon in plant matter and soil. The expansion of canopy leaf area is updated daily by adding the carbon fixed in the leaf carbon pool multiplied by the specific leaf area (SLA) for that crop. Agro-IBIS calculates ET by taking the sum of total canopy transpiration as well as evaporation from soil and leaf surfaces. Each plant functional type has independent parameterizations for physiologic sensitivity to environmental stresses (e.g., water and nitrogen), which include effects of root distribution and key physiologic properties. The simulation of annual crops has been evaluated in several studies (e.g. Donner and Kucharik, 2003; Kucharik, 2003; Kucharik and Brye, 2003; Kucharik and Twine, 2007). In particular, maize water use has been evaluated with surface flux measurements (Kucharik and Twine, 2007) and maize yield has been evaluated with USDA survey data across a 13-state region (Kucharik, 2003). The simulation of miscanthus structure and functioning has also been evaluated (VanLoocke et al., 2010).

2.2. Model development

The algorithm developed to simulate miscanthus by VanLoocke et al. (2010) was modified for the current study to incorporate switchgrass. Key parameters and their associated values in the switchgrass parameterization were incorporated into the model (summarized in Table 1). Switchgrass begins senescence earlier than miscanthus; an additional browning period was incorporated into the switchgrass algorithm before complete senescence occurs to capture this. A rhizome biomass pool was incorporated for both feedstocks to improve belowground carbon dynamics. Miscanthus and switchgrass take 2–5 years to reach full maturity (i.e., ceiling yield) depending upon location (Heaton et al., 2010); to incorporate this, an initial rhizome building period was added in the years following planting. It has also been suggested that miscanthus translocates nutrients and biomass between above-ground biomass and the rhizome at periods during the growing season (Dohleman et al., 2012; Heaton et al., 2010). To accommodate