- **Project title and PI's name and contact information**

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- **Problem and research objective**

Water is a crucial component in agricultural production (Wallace et al., 2000; Chaves et al., 2003; Oliver et al., 2009), the demand for which is predicted to increase in the future (Steduto et al., 2007). There are many uncertainties associated with future water availability, many of which are driven by predicted climatic changes (e.g., Wuebbles and Hayhoe, 2004). However, proposed changes to land use could potentially lead to large-scale alterations in the hydrologic cycle of Illinois and the Midwestern US. One potential land use change that is receiving relatively little attention is the onset of increased renewable energy production. The US 2007 Energy Independence and Security Act requires that production of ethanol from corn grain is capped near current production levels and that the majority of renewable fuels will be produced by cellulosic feedstocks by 2022 (Sissine, 2007). However, cellulosic feedstock production should not result in unsustainable agronomic practices or have negative impacts on ecosystem services, particularly those related to the hydrologic cycle. Little is currently known about the perturbations to the environment that will occur if production of cellulosic feedstocks were to be executed on a large scale (Rowe et al., 2009). This research will provide detailed insight on various bioenergy feedstock production scenarios and the effects of these land use changes on key components of the hydrologic cycle and on water quality.

The majority of the land area in Illinois was once host to tall grass prairies, thus the soils, climate, and topography are well suited for the production of tall perennial grass species. Two candidate species identified as ideal candidates for cellulosic feedstock production for this region are *Miscanthus* × *giganteus* (miscanthus) and *Panicum virgatum* (switchgrass; Heaton et al., 2008). Based on small-scale experiments, it is shown that miscanthus and switchgrass take up more carbon (Stampfl et al., 2007; Davis et al., 2010; Zeri et al., 2011), require less nutrient application (Heaton et al., 2004, 2010), but use more water (Hickman et al., 2010; McIsaac et al., 2010; VanLoocke et al., 2010) than current vegetation. Through small-scale impacts on the timing and rate of evapotranspiration of miscanthus and switchgrass compared to existing land cover, changing the land use to accommodate a perennial grass can have large-scale consequences on many components of the regional hydrologic cycle. The impact of an increase in water use associated with cellulosic biofuel production has been discussed previously (NRC 2008; 2011; McIsaac et al., 2010; Hickman et al., 2010), however, quantification at the State and Regional scale is lacking. This was the motivation for our first objective. Objective 1: Estimation of the total water use, biomass productivity and water use efficiency (WUE) of miscanthus and switchgrass relative to maize.

The goal of this objective was to compare total water use, productivity, and three WUE metrics for two leading cellulosic feedstocks against maize, the currently dominant bioenergy feedstock. The term water use efficiency (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 can be considered an ecosystem service and is an important factor when selecting a cellulosic feedstock (Somerville et al., 2010). A number of different metrics can be used to calculate WUE; for this project we used the following three. First, WUE was calculated based on the total water used in evapotranspiration (ET) to achieve a given harvested biomass, defined as harvest WUE

(HWUE). Second, WUE was calculated as the total water used for the total annual net ecosystem productivity (NEP), which we defined as ecosystem WUE (EWUE). Finally, WUE was calculated based on the total water used for the total net biome productivity (NBP), where NBP is NEP minus the carbon removed at harvest, which we defined as biome WUE (BWUE). This objective allowed for a thorough analysis of the various WUE metrics throughout the Midwest, allowing for identification where ecosystem services for one species (e.g., switchgrass) might be more beneficial than for another species (e.g., miscanthus).

Land use changes to accommodate production of miscanthus and switchgrass are likely to influence more than the quantity of water flowing through various components of the hydrologic cycle. Perennial grasses require less fertilizer than maize (e.g. Heaton et al., 2010). Therefore, the potential exists to decrease the leaching of nitrogen into the water, improving water quality and providing an ecosystem service (Costello et al., 2009; McIsaac et al., 2010; Ng et al., 2010). Alternatively, if the hydrologic cycle is perturbed by an increase in rates of ET, less water flowing though streams and rivers could potentially be more concentrated in pollutants, thereby degrading water quality. In either case, large-scale changes in evapotranspiration and nutrient application compared to existing land cover has the potential to alter the flux of nitrate through the Mississippi River Basin to the Gulf of Mexico. Current research focusing on water quality changes associated with these feedstocks is limited to point measurements of nitrate movement within the soil profile (McIsaac et al., 2010) and watershed scale measurements that do not include validated mechanistic growth and physiology modules for miscanthus and switchgrass (Costello et al., 2009; Ng et al., 2010). This was the motivation for our second objective.
Objective 2: Predict the impact of cellulosic biofuel production on streamflow and nutrient transport in streams, rivers, and discharge from the Mississippi River Basin.

This objective coupled a version of Agro-IBIS developed in objective one with the Terrestrial Hydrology Model with Biogeochemistry (THMB). We drove the model using different scenarios based on establishing a variety of fraction covers of miscanthus and switchgrass in place of the current mosaic of vegetation. This model coupling allowed the excess water in each grid cell to be routed through known streams and rivers throughout the basin and allowed us to quantify changes in streamflow in the region. Through various simulated nutrient applications, we also determined the nitrate leaching from different vegetation types,

The outcome of this research helped us to understand the consequences of land use change to accommodate cellulosic feedstocks grown for renewable energy. Clear benefits in terms of offsetting fossil fuel usage and improving economic development are already widely known, but our research has important implications in driving the best management practices and to help inform producers, policy makers and private and commercial stake holders. Climate also has an unavoidable impact on daily life, from agricultural productivity, to biodiversity, and human health. Thus, understanding the consequences of land use change on climate can help to minimize uncertainties associated with various production scenarios. This research coupled advanced, highly mechanistic ecosystem modeling with state-of-the-art measurements to provide the most defensible and accurate simulations possible before a cellulosic feedstock industry emerges. While the purpose of the research was hypothesis-based and intended for scientific audiences, the model simulations and outputs will be integrated into a web-accessible graphical user interface for use by non-technical users, including the general public.

- **Methodology**

Our research addressed the regional environmental impacts and ecosystem services of cellulosic feedstocks on the Midwest regional hydrologic cycle. Objective 1 was addressed using the Agro-

IBIS (Integrated Biosphere Simulator–Agricultural version; Kucharik and Brye, 2003) ecosystem model, described in detail below, at local and regional scales. Agro-IBIS served as the central model for this project and different vegetation was explicitly represented to accomplish the first objective. For the second objective, the fluxes of water out of the soil column (drainage) as well as nutrients (nitrogen leaching) simulated by Agro-IBIS was routed by the Terrestrial Hydrology Model with Biogeochemistry (THMB; Donner and Kucharik, 2008) through a realistic network of streams through the region. Our research modified Agro-IBIS to simulate the growth and biophysical processes (e.g. water use, and carbon uptake) of miscanthus and switchgrass. We used state-of-the-art sensors to validate the model using the most complete measurements on the carbon, nitrogen and hydrological cycles associated with standard agronomic species (maize and soybean) compared with miscanthus and switchgrass. We coupled Agro-IBIS with THMB in order to route water and nitrogen fluxes in each grid cell through the region to the Gulf of Mexico.

Since Agro-IBIS is a semi-mechanistic model, we used published values for certain physiologically based parameters for each species. However, given the nascent nature of this research, there is a tremendous amount of parameterization that is required where current data does not exist. In this case, we collected the data necessary to parameterize the model using a variety of equipment designed specifically for characterizing key physiological traits associated with vegetation. This includes portable gas exchange systems for measuring key photosynthesis and respiration variables, leaf area meters to determine canopy characteristics, and a range of laboratory based equipment analyzing nitrogen and carbon ratios in the plant tissues. Proper parameterization is critical to maximize the predictive ability of a model, but data for proper validation is equally important. Incorporated into this research project was the opportunity to use equipment that provides ecosystem-scale measurements of carbon, water and energy fluxes using a technique referred to as eddy covariance. This method provides temporal resolution ranging from half-hourly fluxes of water vapor and carbon dioxide for measuring key biogeochemical fluxes. Additional data includes monthly and annual mean streamflow [$m^3 s^{-1}$] and nitrate export [$kg\ yr^{-1}$], daily maximum and annual surface temperature [°C] and precipitation [mm]. We conducted a rigorous validation of the model by comparing the predicted fluxes of key biogeochemical variables against the gold standard in measuring these same fluxes as the data is collected.

The temporal and spatial domain for the second stage of simulations using THMB was the same as the stage one simulations in Agro-IBIS. THMB simulations were run at 5’ × 5’ spatial resolution to resolve the variation in elevation that drives streamflow. Monthly mean values of drainage and nitrate leaching were integrated into the THMB structure, where the water and nutrient was routed through the region to the Gulf of Mexico. For the control simulation, current land use and management practices in the region were represented based on the approach in Donner and Kucharik (2008). Simulations were then conducted using various fractions of land devoted to miscanthus and/or switchgrass relative to current crops to determine consequences of their production on stream flow and water quality. Additional simulations were conducted with varying levels of nutrient application based on predicted management recommendations for each cellulosic feedstock.

- **Principal findings and significance**

The principal findings of this research added considerable insight into water-related ecosystem services associated with large scale production of the key cellulosic bioenergy feedstocks, miscanthus and switchgrass, and can be summarized in three categories: 1) Water Use 2) Water Use Efficiency and 3) Water Quality. The findings with respect to Water Use and Water Use efficiency were produced through the efforts to address objective 1 described above. Through the detailed parameterization and validation of the updated version of Agro-IBIS, we were successfully able to produce the best estimates to date of water use by miscanthus and switchgrass, and the relative gain in carbon for that water use (i.e. Water use efficiency). The results produced from the objective 1 analysis indicated that miscanthus will use more water across the Midwestern US relative to maize (the current dominant feedstock) and switchgrass. However when three different metrics of carbon gain were used to obtain water use efficiency, we showed that miscanthus uses water more efficiently than maize and switchgrass for most of the Midwestern US. We also showed that for belowground carbon production, switchgrass was more water use efficient than maize, despite being less efficient in terms of grain or aboveground production. By putting the water use of these cellulosic feedstocks in the context of their relative carbon gain, this research showed that, if properly implemented, miscanthus could produce more bioenergy and sequester more carbon, getting a much larger return for the water used. This finding is of critical significance given the predicted increased demand on water going into the future.

The principal findings with respect to objective 2 was that the decrease in streamflow associated with the increased rates of water use for miscanthus and switchgrass where minor relative to the large improvements in water quality associated with greatly reduced rates of nitrate leaching. This was driven by the perennial nature of miscanthus and switchgrass, combined with internal nutrient recycling which allows for a more efficient use of nutrients. This reduced the demand for fertilizer and the opportunity for nitrate to leach into streams. Another important finding from objective 2 was that the most aggressive biofuel production scenarios showed the potential for a reduction in nitrate leaching to be great enough to meet the EPA targets for reducing the size of the Gulf of Mexico Hypoxic Zone.

- **Notable achievements**

A key achievement of this research was the development of a modeling framework capable of simulating the hydrologic impacts of cellulosic bioenergy production at the scale of the Mississippi River Basin. It was vital to achieve this large scale framework to make quantitative estimates of the direct impacts of policy and management decisions on water quality and quantity in the Mississippi River Basin. Given the direct relevance of cellulosic biofuels and the Gulf Hypoxic Zone to policy, this research has provided a greatly improved, and highly defensible, method for guiding future policy. Because we were able to combine the agro-ecosystem model directly to the hydrologic transport model, we achieved a tool to assess key water-related issues for bioenergy production in the Midwestern US and the Mississippi River basin. Finally, as new decisions are made, and the cellulosic production system evolves, we will be able to make quantitative estimates as to what the impacts are likely to be, in a way that can inform future policy and management decisions.

- **Students supported with funding**

Andy VanLoocke, Department of Atmospheric Sciences, University of Illinois. Ph.D. awarded in October of 2012. He is current a postdoctoral research associate with the USDA-

ARS and will begin a position as assistant professor in the Department of Agronomy at Iowa State University in January 2014.

- **Publications and presentations**

VanLoocke A, Twine TE, Zeri M, Bernacchi CJ. (2012) A regional comparison of water-use-efficiency for miscanthus, switchgrass and maize. Agricultural and Forest Meteorology, 164, 82-95.

VanLoocke A, (2013) The impact of land-use and global change on water-related agro-ecosystem services in the Midwest US. Ph.D. Thesis, University of Illinois. https://www.ideals.illinois.edu/handle/2142/42334

This research was included in 9 presentations/posters; however none of these were published as conference proceedings.

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