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Perennial biomass production from marginal land in the Upper Mississippi River Basin

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Key words

Switchgrass, *Miscanthus*, biomass production, SWAT, marginal land suitability

Abstract

Marginal land is considered promising for biomass production. However, understanding on biomass crop growth and total biofuel production from this land type is very limited. This study evaluated potential production of switchgrass (*Panicum virgatum*) and *Miscanthus* (*Miscanthus* × *giganteus*) on marginal lands in the Upper Mississippi River Basin (UMRB). A SWAT model with detailed representation of marginal lands and their suitability for growth of the two grasses was setup. Marginal land was defined as cropland and grassland with land capability class 3 to 8. All marginal lands were included as new land covers in the land use map and were preserved when HRUs were defined. The SWAT model was calibrated for flow at 13 sites within the UMRB region at monthly scale. The predicted biomass by growing switchgrass and *Miscanthus* on marginal lands in the study area can produce up to 37% of the 132 billion liter biofuel goal set by the 2010 Energy Independence and Security Act in the US. The simulated flow was lower when marginal lands were converted to grow perennial bioenergy crops. The results from this study improved our understanding on growth of perennial crops on marginal land and their contributions to biofuel development.

1. Introduction

Is there enough land to produce renewable energy and meet food supply simultaneously (Nonhebel, 2005)? This debate on food versus fuel competition started with the expansion of biofuel industries in the 2000s (Rosegrant & Msangi, 2014). Significant amounts of corn (*Zea mays* L.) are utilized for fuel production, resulting in increased corn prices (Ajanovic, 2011). This on-going debate reflects the fact that finding plentiful and proper land for production of biofuel crop is one of the most important tasks in biofuel sustainability (Gopalakrishnan *et al.*, 2009). Among proposed land resources, marginal land is the most promising choice for producing biomass feedstocks (Cai *et al.*, 2011; Campbell *et al.*, 2008; Skevas *et al.*, 2014). Marginal land is less productive than prime farm land. The primary reason is that producing feedstocks on marginal land minimizes the impacts on food supply (Cai *et al.*, 2011; Gopalakrishnan *et al.*, 2011; Liu *et al.*, 2011). In addition, growing biomass crops on marginal land, especially perennial grasses such as switchgrass and *Miscanthus*, is expected to benefit the environment by increasing carbon sequestration (Tilman *et al.*, 2006; Lal, 2006) and reducing non-point source pollution (Blanco-Canqui *et al.*, 2006; Curley *et al.*, 2009; Dabney *et al.*, 2009; Feng *et al.*, 2015; Lee *et al.*, 2012; Gesseesse *et al.*, 2015) comparing to those from crop land. Marginal lands can contribute large amount of biomass (Cai *et al.*, 2011; Campbell *et al.*, 2008). However, predictions in these studies were made under the assumption that yield of biomass grasses on marginal land were homogeneous spatially and consistent across years.

Land suitability indicates the fitness of one land plot for designed purposes, such as growth of specific crops (Elsheikh *et al.*, 2013). The suitability of marginal land for the growth of biomass crops was quite varies a lot. The variation is indicated by the large range of switchgrass yield across large geographical regions in the US (Wullschleger *et al.*, 2010). Feng *et al.*, (2017a) quantified the suitability of marginal land for switchgrass and Miscanthus using a framework based on fuzzy logic theory. Five factors in this framework that limit growth of the two grasses include depth of soil, slope, pH, salinity, and precipitation, were considered in that framework. Besides, the suitability of marginal land is affected by other factors that define marginal land. These factors include economic viability, labor and chemical costs, market price of agricultural products, management options, among others (Peterson and Galbraith, 1932; James, 2010; Liu *et al.*, 2011; Gopalakrishnan *et al.*, 2011). The impacts on biomass yield prediction will eventually affect the prediction of total biomass production from marginal land.

There are two common ways to estimate total biomass production at the watershed or regional scales. One way is to multiply marginal land areas by average reported yields for the candidate biomass crops (Cai *et al.*, 2011; Sudha & Ravindranath, 1999; Tang *et al.*, 2010). The other way is to use biophysical models, such as the Agricultural Policy Environmental eXtender (APEX) model (Feng *et al.*, 2015), Soil and Water Assessment Tool (SWAT) model (Srinivasan *et al.*, 2010b) and the MISCANMOD model (Clifton-brown *et al.*, 2004; Hastings *et al.*, 2009). Using biophysical models is more suitable for predicting biomass production on marginal lands as it accounts for variations in soil, land management, environmental conditions, and climate conditions. In other words, biophysical models can incorporate suitability of marginal land in predicting biomass production at watershed or regional scales.

This study is conducted primarily to improve our understanding on production potential of switchgrass (*Panicum virgatum L.*) and *Miscanthus* (*Miscanthus* × *giganteus*) on marginal lands in the Upper Mississippi River Basin (UMRB) region. Switchgrass and *Miscanthus* are selected as candidate bioenergy crops due to their high and sustainable yield and relatively lower requirements for agricultural chemical applications (Wright & Turhollow, 2010; Zub & Brancourt-Hulmel, 2010). The UMRB region is not only important for traditional crop production, but also a major source of sediment and nutritional losses to the Gulf of Mexico. The importance of this region in biofuel development is also well recognized (Demissie *et al.*, 2012; Srinivasan *et al.*, 2010b; Wu *et al.*, 2012a). Former studies in this region predicted biomass production scenarios of corn land expansion or using corn stover as biomass feedstock (Demissie *et al.*, 2012; Wu *et al.*, 2012b). Evaluation of scenarios using perennial grasses as biomass feedstocks on marginal lands is limited for this region.

The overall goal of this study was to test the hypothesis that growing perennial grasses on marginal lands in the UMRB region will produce significant amount of biomass. Specific goals included: 1) predicting biomass production on marginal lands while incorporating land suitability for switchgrass and *Miscanthus*, and 2) evaluating the impacts of bioenergy crop production on water resources of the region.

2. Methods

2.1 Study area

The UMRB basin covers 7 states (Figure 1) and has a total drainage area of 492,000 km^2. This basin is located in the Corn Belt of the US and has 43% of its area used for corn, soybean (*Glycine max*), and wheat (*Triticum aestivum*) production. Other major land cover types include forests (22%), pasture (16%), water and wetlands (10%), developed areas (8%), and other agricultural crops (1%). These area percentages were calculated with crop database layer (CDL) provided by National Agricultural Statistic Service (NASS) for the 2014 year (USDA, 2014). Fertile soil, adequate water supply and favorite climate in this region make it an important area for food production, especially for corn and soybean (Wu *et al.*, 2012b). The large amount of crop production in this region also provides more than 50% of the US biofuel (Wu *et al.*, 2012b). Almost all current biorefineries use corn grain as feedstock. Only one biorefinery (DuPont, in Nevada, Iowa) uses cellulosic biofeedstock. Several studies have been conducted to test the growth of switchgrass across this region at several locations (Supporting Information, Table S1 and S2).

[Figure 1 Location of the Upper Mississippi River Basin, major land types within this region and reported experimental sites for switchgrass growth]

2.2 Marginal land and their suitability for perennial grass growth

In this study, marginal land was defined as agricultural (corn, soybean, and other agricultural lands) and pasture land that have land capability class (LCC) from 3 to 8 (Feng *et al.*, 2017a). Land types were identified based on CDL provided by NASS (USDA, 2014). LCC information was extracted from soil properties information from the Soil Survey Geographic (SSURGO) database. Details on marginal land area calculation were available in Feng *et al.*, (2017a). Approximately 23% of the UMRB region were identified as marginal lands. The suitability of marginal land for the growth of switchgrass and *Miscanthus* was evaluated using a framework based on fuzzy logic (Feng *et al.*, 2017a). A land suitability index (LSI) map was generated using the framework. The LSI values ranged from 0 for land unsuitable, to 1 for land completely suitable for growth of the two grasses. In this study, LSI for switchgrass and *Miscanthus* were reclassified into three classes: Not suitable (NS, with LSI 0 to 0.3), Moderately suitable (MS, with LSI 0.3 to 0.6) and Highly suitable (HS, with LSI 0.6 to 1.0). The LSI maps were reclassified and embedded into the land use map for setting up the SWAT model.

2.3 SWAT model setup

The SWAT model was developed to evaluate the impacts from changes of land use, management, and climate on crop growth and ecohydrologic processes (Wang *et al.*, 2013, 2016; Wang & Kalin, 2011). This model has been widely used in evaluating impacts from biofuel related scenarios (Demissie *et al.*, 2012; Ng *et al.*, 2010; Srinivasan *et al.*, 2010b; Wu *et al.*, 2012b). Detailed description of the SWAT model is provided in Neitsch *et al.,* (2011). An ArcSWAT2012 (for ArcGIS 10.2, rev635) interface was used to prepare input files for the SWAT model. The ArcSWAT starts with delineating watershed and subareas based on either digital elevation model (DEM) data or a predefined watershed shapefile. Within subareas, HRUs are defined based on land use, soil and slope information. Then, climate and crop management data were added. At last, input tables for the SWAT model was written.

In this study, predefined watershed (5,732 subareas) based on hydrographs (hydrologic unit code, HUC, 12) and DEM layer (30 m) by United States Geographic Survey (USGS) were used in watershed delineation. For the land use data, the map with marginal land suitability information was used. The spatial distribution of suitability classes for switchgrass were very close to those for *Miscanthus* (Feng *et al.*, 2017b). Thus, only one reclassified suitability map (for switchgrass) was used. The final map contained 12 new land cover types (4 major land cover types of marginal land, each with 3 suitability classes) in addition to those originally present in the NASS layer. These new types were added to the crop table in the SWAT2012.mdb file. For the soil data, the spatial map was generated by merging the SSURGO spatial map in the marginal land area and the State Soil Geographic (STATSGO) spatial map at the non-marginal land area. The attributes tables in the STATSGO datasets were exported from the SWAT_US_Soils.mdb file and imported into the SWAT_US_SSURGO_Soils.mdb file. The slopes had two levels: 0-5% and steeper than 5%. While defining the HRUs, marginal land cover types were put into exceptions from 20% thresholds for land use and soil. Finally, 136,079 HRUs were defined, with 84% marginal land HRUs (114,398).

For climate data, daily weather data (precipitation, maximum and minimum temperature) were downloaded for 732 weather stations located within the UMRB region from National Climate Data Center (NCDC, https://gis.ncdc.noaa.gov/). Stations with more than 20% missing data for precipitation were abandoned. At last, 440 stations were used. Missing data in these stations were filled by data from the closest 5 stations located within 50 km of the target station using the Inverse Distance Weighting method. Management practices for corn, soybean, pasture, switchgrass and *Miscanthus* were the same as those used by Feng *et al.* (2015). For switchgrass and *Miscanthus*, a 2- and 3-year establishment periods were assumed based on Feng *et al.*, (2017b), respectively. Tile drainage was installed on corn and soybean HRUs (9,375, 18.2% of the total UMRB area) with soil types having drainage classes of somewhat poor, poor and very poor (based on SSURGO) and slopes less than 2%. Point source and reservoir inputs were prepared with data downloaded from the USGS website. Finally, 136,079 HRUs were generated for the SWAT model at the UMRB region.

2.4 SWAT model calibration and validation

Two steps were used in calibrating the SWAT model. In the first step, a SWAT model with same dataset but less number of HRUs (one HRU for one subarea) was setup. This model was calibrated for streamflow. In the second step, the calibrated parameters were transferred to the finer model with 136,079 HRUs. This approach was used because running the SWAT model with large number of HRUs is time-consuming (Yen *et al*., 2016). However, even though the parameter from the coarse setup provided a base, a lot of tuning was conducted to finally calibrate the model. During the calibration process, the model was first checked by comparing mean and variation of simulated yield of major crops (corn and soybean) with observed yields provided by NASS for 1995 to 2005 in this region. Then, it was calibrated for streamflow against observed data for 13 USGS gauge stations (Table 1) at monthly scale for 1995 to 2000 and validated for 2001 to 2005 with 3 year warm up periods. The calibration and validation were evaluated by the coefficient of determination (R^2) and the Nash-Sutcliffe efficiency (NS) (Equation 1, E1), in which O and P represents for observed and simulated values, respectively and i represents for month in this study. Additional details were provided in section 2 of the supporting information and parameters with their calibrated values were in Table S3 and S4.

$$NS = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (E1)$$

2.5 Scenarios and data analysis

The situation of the UMRB region simulated by the validated model was considered as the baseline scenario. It was then used to simulate two projected scenarios in which switchgrass and *Miscanthus*, respectively, were grown on all marginal lands for 11 years (1995 to 2005). The yield of corn, soybean, switchgrass and *Miscanthus* were summarized separately for HRUs with different marginal land suitability classes. The simulated yield of switchgrass and *Miscanthus* at field scale have been verified in a former paper (Feng *et al.*, 2017b). Total biomass production was calculated by summing up the products of yield and area for each HRU. Total bioethanol was calculated by multiplying total biomass and bioethanol yield of 302 Liter/Mg dry biomass (80 gallon/Mg dry biomass) (Feng *et al.*, 2015). The results for streamflow were analyzed at the watershed outlet, and for evapotranspiration (ET) and soil moisture were evaluated at the HRU level.

3. Results

3.1 Model calibration and validation

Accuracy of the simulated baseline scenario was evaluated in two aspects. The first aspect was the simulated yields of major crops (corn and soybean). Simulated corn grain yield ranged from 0.1 to 11.7 Mg/ha with an average of 8.5 Mg/ha. Simulated soybean yield ranged from 0.1 to 4.0 Mg/ha with an average of 2.6 Mg/ha. The reported yields by NASS for corn ranged 2.3 to 11.3 Mg/ha with an average of 8.6 Mg/ha and for soybean ranged from 1.5 to 3.5 Mg/ha with an average of 2.3 Mg/ha. The second aspect was simulation of flow. The statistics (R2 and NS) for monthly flow at majority sites were over 0.5 (Table 1), indicating good to very good performances of the baseline model (Yen *et al.*, 2016). Comparison of time series between observed and simulated flow and sediment load at the watershed outlet (Mississippi River below Grafton, IL, 05389500) are provided in Figure S1.

[Table 1 here]

3.2 Yield and biofuel production of switchgrass and Miscanthus

The average simulated yields of switchgrass during their post establishment period (from year 3 to year 11) across all marginal lands was 8.2 Mg/ha (Table 2), ranging from 0 to 11.3 Mg/ha. That of *Miscanthus* was 13.3 Mg/ha, ranging from 0 to 16.8 Mg/ha. Distribution of yields during their post establishment periods across all marginal land HRUs with NS, MS, and HS suitability classes are provided in Figure S2 and S3. Distribution of yields for switchgrass and *Miscanthus* showed similar trends across marginal lands with different land suitability classes. Biomass yields of switchgrass on 88% of marginal land HRUs were higher than 5 Mg/ha and of Miscanthus on 90% of marginal land HRUs were higher than 10 Mg/ha, respectively.

[Table 2 here]

Switchgrass yield increased monotonically during its establishment period (year 1 and year 2) and at the beginning (year 3) of the post establishment period as shown in Table

2 and Figure 2. *Miscanthus* yield also increased during its establishment period (year 1 to year 3), but yield during the post establishment period (year 4 to year 11 in this study) was lower than the establishment periods. The yield distribution of each grass was similar across the simulation time and all marginal lands (Figure 2).

[Figure 2 Simulated yield of switchgrass and *Miscanthus* during their pre- and post-establishment periods on marginal land with three suitability classes. LCC stands for Land capability class.]

Based on yield data extracted from literature, biomass produced during the establishment period were not harvested. With yields during the post establishment periods, 96 million Mg biomass could be produced from switchgrass and 160 million Mg from *Miscanthus*. The biomass could be used to produce 29 million and 48 million Liter bioethanol from switchgrass and *Miscanthus* (Table 2), respectively.

3.3 Impacts of growing biomass on hydrology

When marginal land was converted to produce switchgrass and *Miscanthus*, flow and at the outlet of the UMRB basin were reduced through years (Figure 3). Flow values were reduced by 10 to 22% with an average of 16% when marginal land was converted to switchgrass, and by 10 to 30% with an average of 23% when converted to *Miscanthus*, compared to the baseline scenario. At the HRU level, ET was increased (Figure S4), while annual soil moisture content (Figure S5) was decreased by various degrees depends on the whether the crop established or not and on the suitability class of the marginal lands. The changes of ET and soil moisture content were close to each other among marginal land with different suitability classes for both switchgrass and *Miscanthus.*

[Figure 3. Comparison of flow at the outlet of the Upper Mississippi River Basin simulated under scenarios for the baseline, growing switchgrass and growing Miscanthus on all marginal land.]

4. Discussion

This study predicted the contribution of growing switchgrass and *Miscanthus* on marginal land in the UMRB region. Results from this study support the hypothesis that marginal land (23% of land in the UMRB region) are able to contribute significant amount of biofuel for the US (22 to 37% of goal of producing 132 billion liters of biofuel). To the best of our knowledge, this is the first study that simulated the growth of perennial grasses on marginal land in the UMRB region using the SWAT model. Existing models focusing on biomass development scenarios in this region did not exclusively consider marginal lands. Instead, all crop lands were included (Srinivasan *et al.*, 2010a). Other studies estimating perennial grass production with the SWAT model had less detailed representation of the marginal lands (Love & Nejadhashemi, 2011).

This study improved the prediction of biomass production on marginal land in three ways. First, marginal land was represented with great details. The areas of marginal land plots are relatively small in the typical Midwest agricultural landscape. In the step of defining HRUs by the ArcSWAT software, area thresholds of land cover, soil and slope (for example, 5%, 10% and 5% for land, soil and slope, respectively) are applied to reduce the total HRU numbers and save computational time, especially in large scale models (Srinivasan *et al.*, 2010a). These thresholds will result into loss of land cover, soil or slope whose areas are smaller than the areas defined by the thresholds in any subarea. Thus, marginal lands are typically lost because of their small area in land plots in general. In this study, marginal land was embedded into the land use map and added to exception when defining HRUs in the ArcSWAT software. By doing this, ArcSWAT will preserve soil information (from the SSURGO database in this study) irrespective of the land plot area in a subarea. Second, suitability classes of marginal land are represented. This increased flexibility and accuracy for predicting growth of switchgrass and *Miscanthus* on marginal land. Third, the SWAT model used in this study is improved for better simulating growth of perennial crops in terms of annual growth algorithms, crop parameter sets, and their establishment periods (Trybula *et al.*, 2015; Feng *et al.*, 2017b).

There are also some limitations in the method used to set up the SWAT model. The first limitation is the significantly increased computational time. It takes approximately 1 hours to run one year of model simulation using desktop with i7 CPU6700 (3.4GHz) and 16 Gb memory. On computer clusters with Xeon E5 and 8 cores (Conte cluster at Purdue University, West Lafayette, IN), it still takes about 45 minutes to run one year. This brought a lot difficulties in calibrating the model.

The second limitation is the limited capability of the SWAT model to represent suitability of marginal land. The ranges, distribution and average values of simulated yields for the two grasses are similar across three suitability classes (Figure 2, Figure S2 and S3). Among 5 factors considered to determine land suitability, high slope, salinity, and soil pH are the major factors reducing marginal land suitability for growth of the two grasses in the UMRB region (Feng *et al.*, 2017a). However, the SWAT model does not simulate impacts of these factors on crop growth. High slope reduced land suitability by reducing machine operation safety. In the SWAT model, slope was used in calculating surface depression storage depth, time of concentration, streambed sheer stress, lateral hydrologic conductivity, surface area of impounded water body, and slope factor for erosion. These variables, like lateral hydrologic conductivity, will indirectly and slightly affect crop growth by affecting soil water availability. Salinity and pH effects on crop yield are not calculated in the SWAT model. Thus, the suitability of marginal land is not incorporated directly by the SWAT model for these factors. This limitation introduced uncertainties in the predicted biomass production. Total biomass of 59 and 206 million Mg are predicted by multiplying the LSI values, total marginal land areas, and average measured yields of switchgrass (5.4 Mg/ha) and *Miscanthus* (18.6 Mg/ha) in the UMRB region (Feng *et al.*, 2017b). In this study, total biomass of 97 and 159 million Mg are predicted for switchgrass and *Miscanthus*, respectively. The average simulated yields of switchgrass are lower than the average reported yields in this region, while that of *Miscanthus* are higher. The comparison between average simulated and reported yield reflects the impacts from above mentioned limitations of the SWAT model on biomass prediction. Specifically, the yield might be over predicted on marginal land with lower suitability for switchgrass growth.

The predicted impacts on flow at the watershed outlet show similar trends as predicted by other studies on perennial grass production. It has been reported that growing perennial grasses will cause more evaporation and reduce the water availability in the soil based on both measured data and modelling results (Cibin *et al.*, 2015; Feng *et al.*, 2015; McIsaac *et al.*, 2010; VanLoocke *et al.*, 2016; Wu *et al.*, 2012b). However, the predicted impacts require further investigation at field (HRU) scale. This study compared simulated relative changes of evaporation (Figure S4) and soil moisture (Figure S5) across marginal lands with different suitability classes. Due to the limitations on crop growth processes mentioned above, simulated relative changes of these variables are quite close to each other on marginal land with different suitability classes.

The results of this study indicated that additional studies are needed to further facilitate using marginal land for biomass production. The contribution of marginal land for biofuel development can be promising. However, sustainable biomass production requires careful planning to provide stable biomass production as well as minimizing negative environmental impacts. More field experiments for biomass crop growth on marginal lands are required to better understand suitability of marginal land and verify model results. In this study, the simulated production of switchgrass are verified with data from limited locations reported in literature. For *Miscanthus*, field studies in the US are very limited, let alone those on marginal lands. Being widely-used for evaluating impacts from biofuel production (Blanco-Canqui, 2016; Cibin *et al.*, 2015; Wagner & Lewandowski, 2016; Yaeger *et al.*, 2014; Zhou *et al.*, 2015), the SWAT model needs to be further improved by considering impacts from soil salinity and pH on crop growth. This is especially important for evaluating crop growth on marginal land due to their sensitivity from these factors. Besides, marginal land conversion to biomass production took portion of current crop and pasture land for food production. The trade-off and overall impact on food production by using these portion of land for food or biomass production require further analysis on whether the high biomass yield from these portion of land might relieve the pressure of using food produced from prime farmland for bioenergy production (Feng *et al.*, 2017a).

5. Conclusions

Marginal land is a viable choice of land resources for biofuel development, since it can provide large amount of biomass by growing perennial grasses. As predicted in this study, 22% to 37% of the biofuel development goal set in the EISA can be produced by growing switchgrass and *Miscanthus* on marginal lands in the UMRB region. The prediction is made by using a SWAT model incorporating marginal land in great details. The SWAT model provides both the total biomass and yield distribution of perennial grasses, which projects the viability of utilizing marginal land for biomass production. The results of this study will facilitate biofuel development plans with greater details and enhance our understanding on biomass production potential from marginal lands. In addition, the results recommend that improvements are needed for applying the SWAT model in areas suffering salinity and pH problems affecting perennial plant growth.

6. Acknowledgements

This study was funded by the US Department of Energy (Award No. DE-EE0004396) and CENUSA Bioenergy grant (USDA NIFA_AFRI grant No. 2011-68005-30411).

7. References

Ajanovic A. 2011. Biofuels versus food production: Does biofuels production increase food prices? *Energy* **36**: 2070–2076. DOI: 10.1016/j.energy.2010.05.019

Blanco-Canqui H. 2016. Growing Dedicated Energy Crops on Marginal Lands and Ecosystem Services. *Soil Science Society of America Journal* **80**: 845. DOI: 10.2136/sssaj2016.03.0080

Blanco-Canqui H, Gantzer CJ, Anderson SH. 2006. Performance of Grass Barriers and Filter Strips under Interrill and Concentrated Flow. *Journal of Environment Quality* **35**: 1969–1974. DOI: 10.2134/jeq2006.0073

Cai X, Zhang X, Wang D. 2011. Land availability for biofuel production. *Environmental Science and Technology* **45**: 334–339. DOI: 10.1021/es103338e

Campbell JE, Lobell DB, Genova RC, Field CB. 2008. The global potential of bioenergy on abandoned agriculture lands. *Environmental Science and Technology* **42**: 5791–5794. DOI: 10.1021/es800052w

Cibin R, Trybula E, Chaubey I, Brouder SM, Volenec JJ. 2016. Watershed-scale impacts of bioenergy crops on hydrology and water quality using improved SWAT model. *GCB Bioenergy* **8**: 837–848. DOI: 10.1111/gcbb.12307

Clifton-brown JC, Stampfl PF, Jones MB. 2004. Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. *Global Change Biology* **10**: 509–518. DOI: 10.1111/j.1529-8817.2003.00749.x

Curley EM, O'Flynn MG, McDonnell KP. 2009. Nitrate leaching losses from Miscanthus x giganteus impact on groundwater quality. *Journal of Agronomy* **8**: 107–112. DOI: 10.3923/ja.2009.107.112

Dabney SM, McGregor KC, Wilson GV, Cullum RF. 2009. How Management of Grass Hedges Affects their Erosion Reduction Potential. *Soil Science Society of America Journal* **73**: 241. DOI: 10.2136/sssaj2007.0434

Demissie Y, Yan E, Wu M. 2012. Assessing regional hydrology and water quality implications of large-scale biofuel feedstock production in the Upper Mississippi River Basin. *Environmental Science and Technology* **46**: 9174–9182. DOI: 10.1021/es300769k

Elsheikh R, Mohamed Shariff ARB, Amiri F, Ahmad NB, Balasundram SK, Soom MAM. 2013. Agriculture Land Suitability Evaluator (ALSE): A decision and planning support tool for tropical and subtropical crops. *Computers and Electronics in Agriculture* **93**: 98–110. DOI: 10.1016/j.compag.2013.02.003

Feng Q, Chaubey I, Her YG, Cibin R, Engel B, Volenec J, Wang X. 2015. Hydrologic and water quality impacts and biomass production potential on marginal land. *Environmental Modelling and Software* **72**: 230–238. DOI: 10.1016/j.envsoft.2015.07.004

Feng Q, Chaubey I, Engel B, Cibin R, Sudheer KP, Volenec J. 2017a. Marginal land suitability for switchgrass, Miscanthus and hybrid poplar in the Upper Mississippi

River Basin (UMRB). *Environmental Modelling & Software* 93: 356–365. DOI: 10.1016/j.envsoft.2017.03.027

Feng, Q., Chaubey, I., Cibin, R., Engel, B., Sudheer, K.P., Volenec, J., 2017b. Simulating establishment periods of switchgrass and Miscanthus in the soil and water assessment tool (SWAT) *Transactions of the American Society of Agricultural and Biological Engineers*, 60, 1621–1632. doi:10.13031/trans.12227.

Gessesse B, Bewket W, Bräuning A. 2015. Model-Based Characterization and Monitoring of Runoff and Soil Erosion in Response to Land Use/land Cover Changes in the Modjo Watershed, Ethiopia. Land Degradation & Development 26: 711–724. DOI: 10.1002/ldr.2276

Gopalakrishnan G, Cristina Negri M, Snyder SW. 2011. A Novel Framework to Classify Marginal Land for Sustainable Biomass Feedstock Production. *Journal of Environment Quality* **40**: 1593. DOI: 10.2134/jeq2010.0539

Gopalakrishnan G, Negri MC, Wang M, Wu M, Snyder SW, Lafreniere L. 2009. Biofuels, land, and water: a systems approach to sustainability. *Environmental science & technology* **43**: 6094–6100. DOI: 10.1021/Es900801u

Hastings A, Clifton-brown J, Wattenbach M, Mitchell CP, Stampfl P, Smith P. 2009. Future energy potential of Miscanthus in Europe. *GCB Bioenergy* **1**: 16. DOI: 10.1111/j.1757-1707.2009.01012.x

James L. 2010. Theory and Identification of Marginal Land and Factors Determining Land

Use Change (Master Thesis). Available from ProQuest Dissertations and Theses Database (ProQuest Document ID 1697511479)

Lal R. 2006. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. Land Degradation & Development 17: 197–209. DOI: 10.1002/ldr.696

Lee J, Pedroso G, Linquist BA, Putnam D, van Kessel C, Six J. 2012. Simulating switchgrass biomass production across ecoregions using the DAYCENT model. *GCB Bioenergy* **4**: 521–533. DOI: 10.1111/j.1757-1707.2011.01140.x

Liu TT, McConkey BG, Ma ZY, Liu ZG, Li X, Cheng LL. 2011. Strengths, weaknessness, opportunities and threats analysis of bioenergy production on Marginal Land. *Energy Procedia* **5**: 2378–2386. DOI: 10.1016/j.egypro.2011.03.409

Love BJ, Nejadhashemi AP. 2011. Water quality impact assessment of large-scale biofuel crops expansion in agricultural regions of Michigan. *Biomass and Bioenergy* **35**: 2200–2216. DOI: 10.1016/j.biombioe.2011.02.041

McIsaac GF, David MB, Mitchell CA. 2010. Miscanthus and Switchgrass Production in Central Illinois: Impacts on Hydrology and Inorganic Nitrogen Leaching. *Journal of Environmental Quality* **39**: 1790–1799. DOI: 10.2134/jeq2009.0497

Ng TL, Eheart JW, Cai X, Miguez F. 2010. Modeling miscanthus in the Soil and Water Assessment Tool (SWAT) to simulate its water quality effects as a bioenergy crop. *Environmental Science and Technology* **44**: 7138–7144. DOI: 10.1021/es9039677

Nonhebel S. 2005. Renewable energy and food supply: Will there be enough land? *Renewable and Sustainable Energy Reviews* **9**: 191–201. DOI: 10.1016/j.rser.2004.02.003

Peterson, G. M., & Galbraith, J. K. 1932. The concept of marginal land. *Agricultural & Applied Economics Association*, 14(2), 295–310.

Rosegrant MW, Msangi S. 2014. Consensus and Contention in the Food-Versus-Fuel Debate. *Annual Review of Environment and Resources* **39**: 271–294. DOI: 10.1146/annurev-environ-031813-132233

Skevas, T, Swinton, SM, & Hayden, NJ. 2014. What type of landowner would supply marginal land for energy crops? *Biomass and Bioenergy*, **67**, 252–259. http://doi.org/10.1016/j.biombioe.2014.05.011

Srinivasan R, Zhang X, Arnold J. 2010a. SWAT ungaged: Hydrological budget and crop yield predictions in the Upper Mississipp River basin. *Transactions of the American Society of Agricultural and Biological Engineers* **53**: 1533–1546. DOI: 10.13031/2013.34903

Srinivasan R, Zhang X, Arnold JR. 2010b. SWAT Ungauged: Hydological Budget and Crop Yield Predictions in Upper Mississippi River Basin. *Transactions of ASABE* **53**: 1533–1546

Sudha P, Ravindranath N. 1999. Land availability and biomass production potential in India. *Biomass and Bioenergy* **16**: 207–221. DOI: 10.1016/S0961-9534(98)00083-X

Tang Y, Xie J-S, Geng S. 2010. Marginal land-based biomass energy production in China. *Journal of integrative plant biology* **52**: 112–21. DOI: 10.1111/j.1744-7909.2010.00903.x

Tilman D, Hill J, Lehman C. 2006. Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science* **314**: 1598–1600. DOI: 10.1126/science.1133306

Trybula EM, Cibin R, Burks JL, Chaubey I, Brouder SM, Volenec JJ. 2015. Perennial rhizomatous grasses as bioenergy feedstock in SWAT: Parameter development and model improvement. *GCB Bioenergy* **7**: 1185–1202. DOI: 10.1111/gcbb.12210

USDA National Agricultural Statistics Service Cropland Data Layer. 2014. Published crop-specific data layer [Online]. Available at https://nassgeodata.gmu.edu/CropScape/ (accessed May 2015). USDA-NASS, Washington, DC.

VanLoocke A, Twine TE, Kucharik CJ, Bernacchi CJ. 2016. Assessing the potential to decrease the Gulf of Mexico hypoxic zone with Midwest US perennial cellulosic feedstock production. *GCB Bioenergy*. DOI: 10.1111/gcbb.12385

Wagner M, Lewandowski I. 2016. Relevance of environmental impact categories for perennial biomass production. *GCB Bioenergy*. DOI: 10.1111/gcbb.12372

Wang R, Bowling LC, Cherkauer KA. 2016. Estimation of the effects of climate variability on crop yield in the Midwest USA. *Agricultural and Forest Meteorology* **216**: 141–156. DOI: 10.1016/j.agrformet.2015.10.001

Wang R, Kalin L. 2011. Modelling effects of land use/cover changes under limited data.

Ecohydrology **4**: 265–276. DOI: 10.1002/eco.174

Wang R, Kalin L, Kuang W, Tian H. 2014. Individual and combined effects of land use/cover and climate change on Wolf Bay watershed streamflow in southern Alabama. *Hydrological Processes* **28**: 5530-5546. DOI: 10.1002/hyp.10057

Wright L, Turhollow A. 2010. Switchgrass selection as a "model" bioenergy crop: A history of the process. *Biomass & Bioenergy* **34**: 851–868. DOI: 10.1016/j.biombioe.2010.01.030

Wu M, Chiu Y, Demissie Y. 2012a. Quantifying the regional water footprint of biofuel production by incorporating hydrologic modeling. *Water Resources Research* **48**: W10518. DOI: 10.1029/2011WR011809

Wu M, Demissie Y, Yan E. 2012b. Simulated impact of future biofuel production on water quality and water cycle dynamics in the Upper Mississippi river basin. *Biomass and Bioenergy* **41**: 44–56. DOI: 10.1016/j.biombioe.2012.01.030

Wullschleger SD, Davis EB, Borsuk ME, Gunderson CA, Lynd LR. 2010. Biomass production in switchgrass across the United States: Database description and determinants of yield. *Agronomy Journal* **102**: 1158–1168. DOI: 10.2134/agronj2010.0087

Yaeger MA, Housh M, Cai X, Sivapalan M. 2014. An integrated modeling framework for exploring flow regime and water quality changes with increasing biofuel crop production in the U.S.Corn Belt. *Water Resources Research* **50**: 9385–9404. DOI:

10.1002/2014WR015700

Yen, H, White, MJ, Arnold, JG, Keitzer, SC, Johnson, MV, Atwood, JD, et al. 2016. Western Lake Erie Basin: Soft-data-constrained, NHDPlus resolution watershed modeling and exploration of applicable conservation scenarios. *Science of The Total Environment*, 569, 1265–1281. http://doi.org/10.1016/j.scitotenv.2016.06.202

Zhou X “Vivian,” Clark CD, Lambert DM, English BC, Larson JA, Boyer CN. 2015. Biomass supply and nutrient runoff abatement under alternative biofuel feedstock production subsidies. *Agricultural Systems* **139**: 250–259. DOI: 10.1016/j.agsy.2015.08.002

Zub HW, Brancourt-Hulmel M. 2010. Agronomic and physiological performances of different species of Miscanthus, a major energy crop. A review. *Agronomy for Sustainable Development* **30**: 201–214. DOI: Doi 10.1051/Agro/2009034

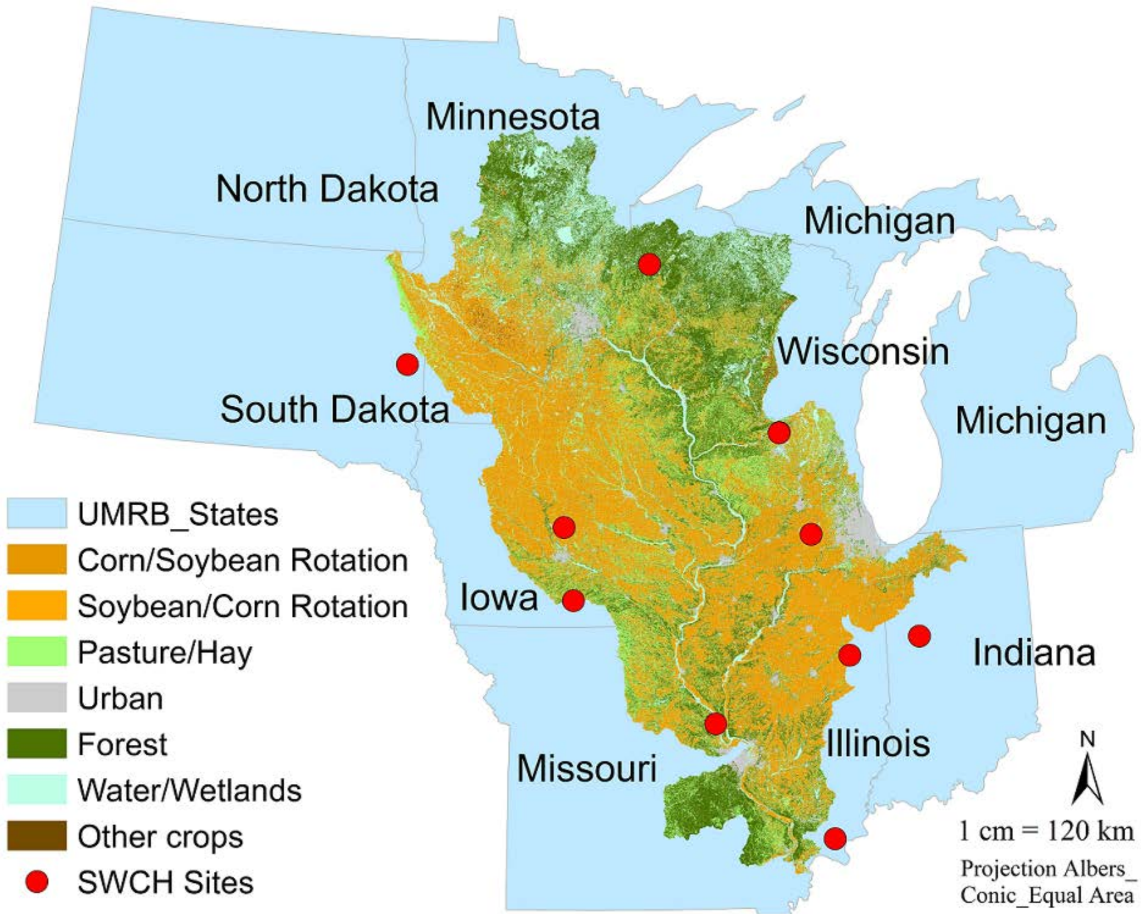

Figure 1: Location, major land use types and fields for switchgrass (SWCH) sites of the Upper Mississippi River Basin

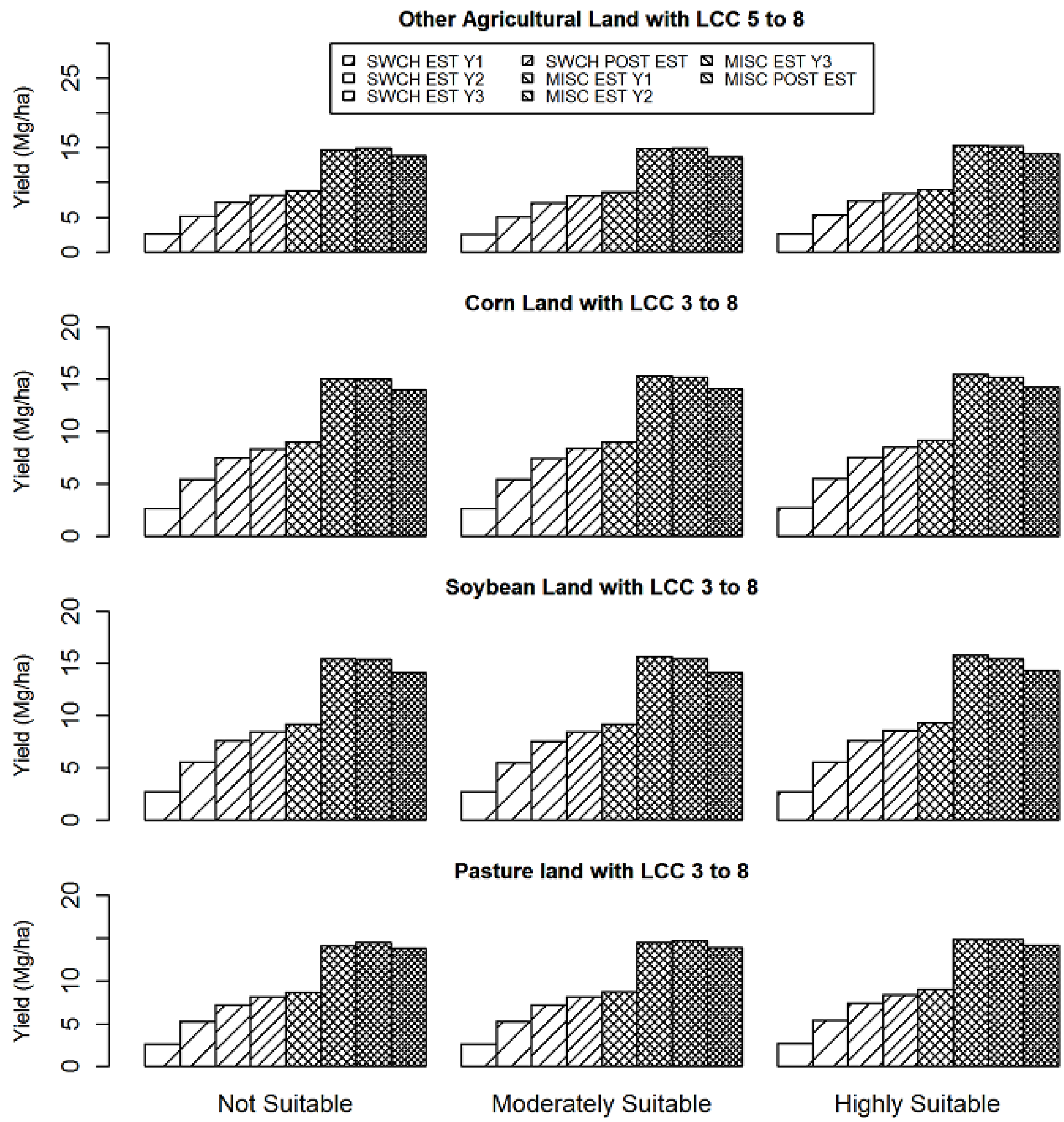

Figure 2: Simulated yield of switchgrass and Miscanthus during their pre- and post-establishment periods on marginal land with three suitability classes. LCC stands for Land capability class

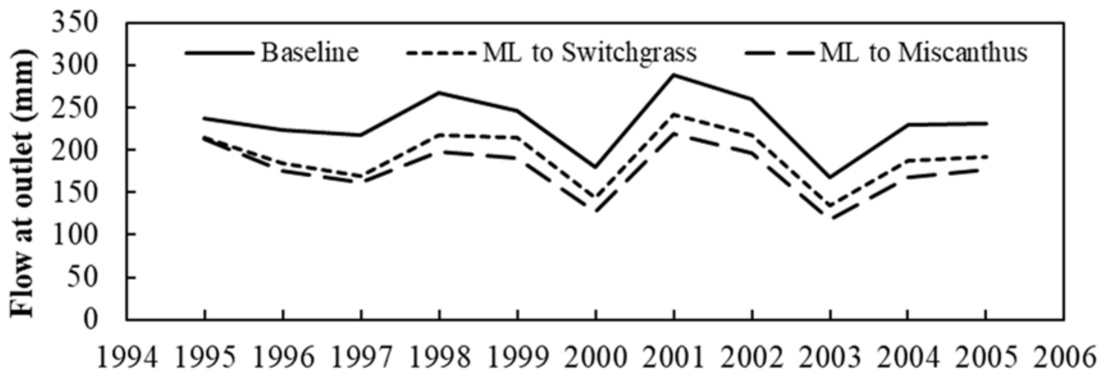

Figure 3: Comparison of flow at the outlet of the Upper Mississippi River Basin simulated under scenarios for the baseline, growing switchgrass and growing Miscanthus on all marginal land

Table 1 Monthly calibration/validation statistics (Coefficient of determination, R^2 and the Nash-Sutcliffe coefficiency, NS) for flow at various stations in the Upper Mississippi River Basin

No.	Station	USGS Gauge No.	Calibration (Monthly)		Validation (Monthly)	
			R^2	NS	R^2	NS
1	Mississippi river at St. Paul, MN	05331000	0.67	0.77	0.60	0.78
2	Minnesota River near Jordan, MN	05330000	0.90	0.94	0.94	0.95
3	St. Croix River at St. Croix Falls, WI	05340500	0.63	0.74	0.72	0.80
4	Chippewa River at Durand, WI	05369500	0.66	0.72	0.65	0.68
5	Mississippi River at McGregor, IA	05389500	0.71	0.73	0.69	0.78
6	Wisconsin River at Muscoda, WI	05407000	0.44	0.63	0.45	0.63
7	Mississippi River at Clinton, IA	05420500	0.73	0.75	0.64	0.76
8	Skunk River at Augusta, IA	05474000	0.81	0.84	0.72	0.78
9	Iowa River at Wapello, IA	05465500	0.71	0.74	0.65	0.66
10	Rock River near Joslin, IL	05446500	0.64	0.71	0.43	0.61
11	Des Moines River at Keosauqua, IA	0.490500	0.56	0.61	0.52	0.54
12	Mississippi River below Grafton, IL	05587455	0.85	0.87	0.74	0.80
13	Illinois River at Valley City, IL	05586100	0.66	0.69	0.66	0.73

Table 2 Average yield of switchgrass and *Miscanthus* and bioethanol potential from marginal lands (ML) in the Upper Mississippi River Basin

	Year	Not Suitable ML (Mg)	Moderately Suitable ML (Mg)	Highly Suitable ML (Mg)	Total Biomass (Million Mg)	Total Biofuel (Billion Liter)
Switchgrass	Year 1	2.7	2.7	2.7		
	Year 2	5.2	5.1	5.4		
	Year 3	7.0	6.9	7.2		
	Post Establish	8.1	8.0	8.5	97	29
Miscanthus	Year 1	8.7	8.5	9.0		
	Year 2	15.3	15.1	16.1		
	Year 3	14.7	14.4	15.1		
	Post Establish	13.2	13.1	13.7	159	48