Hydrologic/water quality impacts and biomass production potential on marginal land

Qingyu Feng¹, Indrajeet Chaubey^{1,2*}, Young Gu Her^{1,4}, Cijin Raj¹, Bernie Engel¹, Jeffery Volenec³, Xiuying Wang⁴.

¹Agricultural and Biological Engineering, Purdue University, 225 South University Street, West Lafayette, IN 47907, USA

²Department of Earth Atmospheric Planetary Science, Purdue University, 550 Stadium Mall Drive, West Lafayette, IN, 47907

³Department of Agronomy, Purdue University, 915 West State Street, West Lafayette, IN, 47907, USA

⁴Blackland Research & Extension Center, Texas A&M Agrilife Research, 720 East Blackland Road, Temple, TX 76504, USA

*Corresponding author: Email: ichaubey@purdue.edu; phone: 1(765)-494-5013; Fax: 1(765)496-1115

Abstract

Marginal land is proposed as viable land resources for biofuel production. However, environmental impacts of perennial biomass production on marginal lands is not clear. This study defined three marginal land types and assessed their availability and potential for biofuel production in the St. Joseph River watershed. The potential impacts were evaluated using the Agricultural Policy/Environmental eXtender (APEX) model. The total area of marginal land was estimated to be 611 km² covering 21.7% of the watershed. 161 and 207 million liters of bioethanol could be produced from the marginal land utilizing switchgrass and *Miscanthus*, respectively. Converting marginal land currently under corn/soybean production to switchgrass and *Miscanthus* reduced water yield by 13.4-36.3% and improved water quality by reducing soil erosion by 27% to 98%. Similarly, total nitrogen losses were reduced by 30-91% and total phosphorus losses were reduced by 65-76%, respectively, at the field scales under various energy crop production scenarios.

- Nitrogen and phosphorus losses will generally be reduced at field scale.

Key words:

Switchgrass, *Miscanthus*, APEX, hydrologic/water quality impacts, bioenergy production, marginal land

1. Introduction

Marginal land has been proposed as a viable choice for producing biomass for advanced biofuels (Tilman et al., 2006; Cai et al., 2010; Gopalakrishnan et al., 2011). In the U.S., the Renewable Fuel Standard of 2010 (RFS2) mandated that 132 billion liters of renewable fuel by 2022 should be used in the transport sector (U.S. Environmental Protection Agency, 2010). To meet this goal, the renewable fuel production should be increased 2.7 times by 2022 from the production of 2014 (49 million liters) (Renewable fuel association, 2015). Choice of land resources is important for producing adequate biomass to meet biofuel development goals. The United States Department of Agriculture estimated that 27 million acres of cropland would be required to produce adequate biomass for meeting biofuel production goals (United States Department of Agriculture, 2010). Currently 35% of corn produced in the U.S. is used as feedstock for ethanol conversion (Downing et al., 2011). Further conversion of cropland to produce biomass for advanced biofuel could intensify impacts on food provisioning (Pimentel et al., 2009). Thus, marginal land is proposed for biofeedstock production because it could reduce land competition among biofuel, food, and feed production (Robertson et al., 2008; Cai et al., 2010; Kang et al., 2013a).

Marginal land has been defined in different ways across disciplines at various spatial and temporal scales (Tang et al., 2010; Liu et al., 2011; Kang et al., 2013b). For biomass production, marginal land is generally considered as land that is not actively engaged in agricultural production and could be used for biomass production without competition between food and fuel, especially perennial grasses such as switchgrass (*Panicum virgatum*) and *Miscanthus* (*Miscanthus x giganteus*) (Woodson, 2011; Bonin and Lal, 2014). The proposed definition of marginal land for biomass production includes degraded land (Campbell et al., 2008), low productivity land (Cai et al., 2010), environmentally marginal land (Gopalakrishnan et al., 2011), land with Land Capability Class (LCC) 3 to 7 (Gelfand et al., 2013), and land located along buffer areas (Engel et al., 2010). Estimates of different marginal land types' spatial distribution

1 and biofuel production potentiality are generally conducted at larger spatial scales such as state
2 (Gopalakrishnan et al., 2011), regional, and global (Cai et al., 2010). Marginal land availability
3 may vary depending on marginal land definitions, data types and sources for area estimation,
4 scope of research, and landscape properties (Cai et al., 2010). Methods used to estimate marginal
5 land at a larger scale may not be applicable at smaller scales due to difference in precision of
6 data required. Similarly, each research develops and uses its own marginal land definition
7 suitable for its objectives and focuses. Thus, availability of marginal land should be estimated
8 based on proper selection of data sources and clear definitions in order to provide reasonable
9 estimates of marginal land areas available for biofuel production.

10 Contribution of marginal land to biofuel development also depends on yields of biomass species
11 under consideration. Switchgrass and *Miscanthus* have been proposed as two promising
12 dedicated biomass crops (McLaughlin et al., 2004). Switchgrass, native to the U.S., has low
13 agricultural input requirements (fertilizer and management) and high yield potential
14 (McLaughlin et al., 2004). It has also been reported that switchgrass can grow well on marginal
15 land (Woodson, 2011). *Miscanthus* could have higher biomass yield than switchgrass (Heaton et
16 al., 2004; Heaton et al., 2008), but can be difficult to establish due to its rhizome-based
17 propagation (Zub and Brancourt-Hulmel, 2010). These two grasses were evaluated as potential
18 biomass feedstock in this study because of their high yield potentials.

19 Another reason for selecting perennial cellulosic grasses for biofeedstock production is
20 their expected environmental co-benefits (Nelson et al., 2006; Costello et al., 2009;
21 Gopalakrishnan et al., 2009). Growing perennial grass like switchgrass and *Miscanthus* can
22 impact hydrology and water quality (Ng et al., 2010; Cibirin et al., 2012; Wu et al., 2012b),
23 ecological conditions (biodiversity and wildlife habitat), and ecosystem services (carbon
24 sequestration). The impacts are spatially varied (Elobeid et al., 2013) and could be either positive
25 or negative, largely depending on the properties of land cover types and management practices
26 implemented (Engel et al., 2010). For example, increased evapotranspiration (ET) is expected
27 with conversion of annual grain crops to perennial grasses such as switchgrass and *Miscanthus*
28 due to their extended growing season. This may reduce soil moisture content and affect regional
29 water resources (Hickman et al., 2010; McIsaac et al., 2010; Love and Nejadhashemi, 2011). Soil
30 erosion could be alleviated with perennial grasses thereby reducing the amounts of sediment in
31 streams. Nutrient loss is also expected to be reduced by growing switchgrass and *Miscanthus*

when compared to annual row crops (McIsaac et al., 2010; Ng et al., 2010). However, marginal land is generally considered to pose higher environmental risks because it often slopes (Wiegmann et al., 2008). Potential environmental impacts are essential information to support policies and decisions targeting sustainable biofuel development. However, understanding on the environmental impacts from biofeedstock production on marginal land is very limited, especially at the watershed scale. Thus, it is necessary to conduct an integrated evaluation of impacts on hydrology and water quality with a focus on cultivating marginal land for second generation biofeedstock production.

The study aims to estimate the impacts of growing perennial biomass crops on marginal land in the St. Joseph River watershed. The specific goals included: 1) assessing marginal land availability in the watershed, 2) estimating total bioethanol productivity from marginal land in the watershed, and 3) quantifying the potential impacts of marginal land biomass production scenarios on watershed hydrology and water quality.

2. Methodology

2.1 Study site description

This study was conducted in the St. Joseph River Watershed located in the Midwest U.S. (Figure 1), which is a region expected to play an important role in producing biomass for biofuel development in the U.S. The area of the St. Joseph River watershed is 2,800 km². Land cover types in the watershed include corn/soybean land (37%), grassland (26%), forest land (12%), other agricultural land (6%), developed land (10%), wetland (8%), and open water (1%) according to the Cropland Data Layer 2010 (CDL 2010) obtained from National Agriculture Statistic Service (NASS) (<http://nassgeodata.gmu.edu/CropScape/>). The major soil texture in the watershed is loam and fine loam, which takes 81% of the watershed area. Slopes in the watershed are normally gentle, with 57% of the watershed area is less than 2%, and another 36% of the area has slopes between 2% and 5%. The remaining 7% of area has slopes steeper than 5%. Average annual precipitation in the watershed is about 1,000 mm based on measured data from 1995 to 2009 (obtained from National Climatic Data Center, <http://www.ncdc.noaa.gov/>).

Figure 1. The St. Joseph River and Matson Ditch watersheds (the Matson Ditch watershed is a subwatershed used in model calibration, Details was provided in Section 2.3.3).

2.2 Marginal land identification

Three types of marginal land were included in this study. Type 1 marginal land was defined as cropland (corn/soybean) and grassland (pasture, hay, and range land in CDL 2010) with LCC 3 and 4. While defining the terms for renewable biomass standards, RFS2 also restricted that renewable biofuel should come from only current cropland, grassland, and land enrolled in the Conservation Reserve Program (CRP). However, cultivation practices on CRP lands were restricted to limited grazing and maintenance, and commercialized cultivation is not allowed (U.S. Government Information, 2014). Thus, only cropland and grassland were selected for marginal land in this study. LCC is a categorizing system that classifies soils into 8 classes according to the suitability for crop cultivation, which decreases from class 1 to class 8. LCC 1 to 4 are considered suitable for cultivation, and LCC 5 to 8 are classified as unsuitable. LCC 3 and 4 were selected because they were considered marginally suitable for row-crop cultivation. This definition has also been used in other studies (Hamdar, 1999, Gelfand et al., 2013). In this study, marginal land was identified based on the CDL2010 and Soil Survey Geographic (SSURGO) (<http://datagateway.nrcs.usda.gov/>) dataset prepared for the watershed.

Type 2 marginal land was defined as land located within 10 m buffer areas along streams in the watershed. Buffer strips were recommended to be suitable for biomass production by Tang et al., (2010) due to their potential to reduce runoff and improve water quality. Stream line data downloaded from National Hydrographic Dataset (NHD) were used in delineating the stream buffer areas. Forest and developed land areas according to CDL2010 were excluded from the buffer area marginal land. Forest area was excluded in this type of land because of its ecological importance and developed land was excluded due to land conversion feasibility.

Forest land located within 50 m buffer of corn/soybean land was defined as Type 3 marginal land. Forest land was not recommended by RFS2 for biomass production. However, deforestation is possible when the pressure from food and fuel production increased. This scenario was included as an extreme case for biofuel development. All mapping was conducted with ArcGIS® software by ESRI (www.esri.com).

2.3 Model setup

2.3.1 APEX model description

APEX is a physically based model for field or small watershed scale simulation (Williams and Izaurralde, 2006). The model was developed to evaluate the impact of long-term agricultural practices on hydrology, soil erosion, nutrient loss (including nitrogen, phosphorus, moving in water or combined with soil) (Williams and Izaurralde, 2006, Gassman et al., 2010). For the simulation, a watershed is divided into subareas, which are assumed to be homogeneous in soil, management practice, and geographic conditions (slope). The model requires weather, soil, field management, and site geographic information as input data and calculates hydrology and water quality variable values for each subarea on a daily basis. Simulation outputs for subareas can be routed to the watershed outlet. Detailed description for the APEX model can be obtained from Gassman *et al.* (2010).

2.3.2 Model setup

In this study, subareas for the study area were delineated through a land-plot configuration procedure, which defined a subarea as a plot having unique combination of land cover and soil types. The subarea delineation using this procedure ensured that all soil or land use types were preserved and included in the analysis. A total of 193,097 subareas were delineated by overlaying CDL2010 and SSURGO datasets. Each subarea was simulated using the APEX model.

The second step was to prepare input files for each subarea in the watershed. A set of input files required for APEX was prepared for each subarea delineated in the first step. Parameters specified for corresponding subarea in input files and source of data for calculating their values were provided in Supplementary Table A.1. There were several hydrologic and soil erosion processes simulation options available in APEX. This study used the Green-Ampt method (Green and Ampt, 1911) for infiltration, the Penman-Monteith (Monteith, 1965) method for potential evapotranspiration (PET) (Williams et al., 2012), and Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) for soil erosion simulation. Management practices for the major land use types (corn, soybean) and the two targeted biofeedstock crops (switchgrass, *Miscanthus*) were provided in Supplementary Table A.2.

2.3.3 Model calibration

A proxy calibration strategy, in which calibrated input parameters from a proxy watershed or a partial watershed are transferred to the target watershed or the entire watershed, was used in this study due to data limitations. The Matson Ditch watershed (50 km²) (Figure 1) within the St. Joseph River watershed was selected for model calibration. APEX calibration was conducted using daily stream flow and monthly total nitrogen (TN) loss from this watershed. Data from the growing season of April to November of 2006 were used for calibration, and data from April to November of 2007 and 2008 were used for validation. Model performance was evaluated using the coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NS_{eff}). The calibration was conducted by only adjusting parameters at a subarea level, which were listed in the Supplementary Table A.3. The calibrated parameters values were transferred to each subarea of the St. Joseph River watershed, and then the calibrated model was used as the baseline in the following scenario analyses.

2.4 Biomass production scenarios

Eight biofuel production scenarios were developed and evaluated with perennial grasses (switchgrass and *Miscanthus*) as candidate energy crops (Table 1). Bioethanol production from switchgrass and *Miscanthus* were estimated using crop yield simulated with APEX model. Hydrologic and water quality variables were evaluated for each scenario at two scales: marginal land and watershed scales. Marginal land scale values were calculated as area weighted average over marginal land subareas, while watershed scale values were calculated as area weighted average over all subareas, including marginal land and non-marginal land subareas.

Table 1 Biofuel production scenarios on marginal land and estimated biofuel production

Scenarios	Type1 (LCC 3&4)		Type 2 (10m stream buffer)	Type 3 (50m Forest around corn/ soybean)	Biofuel crop area (km ²)	Biofuel (APEX simulated yield) (Million liters)
	Grassland	Cropland				
B	-	-	-	-	0	0
SGLCC	S	-	-	-	230.1	60.85
MGLCC	M	-	-	-	230.1	78.39
SCLCC	-	S	-	-	255.5	66.45
MCLCC	-	M	-	-	255.5	85.04
SB10	-	-	S	-	1.4	0.38
MB10	-	-	M	-	1.4	0.48
SF	-	-	-	S	123.6	33.77
MF	-	-	-	M	123.6	43.50
Total Marginal land area					610.6	
Total biofuel from switchgrass						161.45
Total biofuel from <i>Miscanthus</i>						207.40

Notes:

1. B: baseline scenario
2. Name conventions for other scenarios: S and M stands for switchgrass and *Miscanthus* respectively. GLCC and CLCC stands for Grassland and Cropland with Land Capability Class 3 and 4. B10 stands for Buffers with a width of 10m alongside stream lines. F stands for forest land located within 50 meter around current corn/soybean land.
3. APEX: Agricultural Policy/Environmental eXtender model
4. Yield values simulated by the APEX model varied among subareas. The average yield values for switchgrass and *Miscanthus* were 8.4 Mg/ha and 10.1 Mg/ha, respectively.
5. Biofuel volume was calculated as the products of biofuel crop area, yield, and bioethanol conversion rate of 85 gal/biomass (dry ton) (Downing et al., 2011). The same bioethanol conversion rate was used for switchgrass and *Miscanthus*.
6. GLCC and CLCC belong to type 1 marginal land. GLCC takes 47% and CLCC takes 53% of type 1 marginal land. B10 belongs to type 2 marginal land, which consisted of 40% cropland and 60% grassland. F belongs to type 3 marginal land, with all areas as forest land.

3. Results and discussion

3.1 Spatial distribution of marginal land in the St Joseph River watershed

Marginal land areas identified based on the three definitions were mapped for St. Joseph River watershed (Table 1). Of them, summed marginal land areas of all three types were 610.6 km², 21.7% of the watershed area. Majority of marginal land came from type 1 and type 3 marginal land. The area of type 2 marginal land is limited for the watershed. A substantial portion of original land cover types in the watershed were classified as marginal land. In the study watershed, about 23.3% of corn/soybean land, 30.1% of grassland, and 23.5% of the forest land were identified as marginal land.

The spatial distributions of three types of marginal land are presented in Figure 2. Types 1 and 3 marginal lands were highly fragmented across the watershed with small unit areas. For example, the total area of cropland with LCC 3 and 4 was 255.5 km², which contained 15,315 land plots. The areas of single plots ranged from 0.0009 km² to 0.7 km², and about 9,340 single plots had areas smaller than 0.01 km². The total area of these 9,340 plots was 36.5 km², only about 15% of total area (255.5 km²) of cropland with LCC 3 and 4. A fragmented distribution of marginal land was expected because of the high variability of soil characteristics in the region.

Figure 2 Distribution of 3 types of marginal land in St. Joseph River watershed: Type 1 marginal land (Left): cropland (corn and soybean) and grassland (pasture, hay and range) with Land Capability Class (LCC) 3 and 4; Type 2 marginal land (Middle): Land located within buffer of 10 m width along main streamlines; Type 3 marginal land (Right): land located within 50 m buffer around corn and soybean land.

The fragmented feature combined with other potential limitations of marginal land (such as low soil quality, small plot area) added uncertainties to the results of availability presented in this study. Plots that have smaller areas (for example, only one to several pixels of 30 by 30 m on the map) might not be suitable for biomass cultivation if they could not be economically managed. In addition, the existence of conservation practices such as tile drainage and erosion control practices might have eliminated some of the existing limitations of Type 1 marginal lands and made them non-marginal land.

3.2 Model calibration results

Streamflow and TN simulations of the APEX model were calibrated and validated at the outlet of the Matson Ditch watershed (Figure 3). The model simulated the daily stream flow with an R^2 of 0.55 and NS_{eff} of 0.53 during the calibration period and R^2 of 0.56 and NS_{eff} of 0.53 in the validation period. The model performance statistics indicated that the daily flow prediction of the model was “satisfactory” in both calibration and validation periods (Moriassi et al., 2007). The model simulated monthly TN loads with R^2 of 0.64 and NS_{eff} of 0.62 in the calibration period and R^2 of 0.93 and NS_{eff} of 0.90 in the validation period, indicating the TN simulation of the APEX model for the Matson Ditch watershed also was “satisfactory” (Moriassi et al., 2007).

Figure 3 Time series of observed and simulated flow (A) and Total Nitrogen (B) at Matson Ditch watershed for calibration (April to November of 2006) and validation periods (April to

November of 2007 and 2008). The higher observed nitrogen loss in May 2006 than observed and simulated nitrogen loss in May 2007 and 2008 could be probably due to a delay of nitrogen fertilizer application in May 2006, while the model assumed that nitrogen fertilizer was applied in April 22 for all three years (Supplementary Table A2). The higher observed and simulated nitrogen loss in April 2007 than in April 2006 and 2008 could be due to higher precipitation in this month.

3.3 Bioethanol production potential from marginal lands

Table 1 presented the total bioethanol production that can be obtained from all the marginal land estimated based on the three definitions. The total bioethanol potential from the marginal land in the watershed was estimated as 161 million liter from switchgrass and about 207 million liter from *Miscanthus* (Table 1).

In this study, crop parameter values used for APEX simulation of switchgrass and *Miscanthus* were adapted from field measurements which were made for upland switchgrass and for *Miscanthus x giganteus* (Trybula et al., 2014). A comparison was made between APEX simulated and measured yield from field experimental sites for the corresponding types of the biofeedstock crops. A list of measured yield values for switchgrass and *Miscanthus* from existing field sites across the U.S. were obtained from literature review (Provided in Supplementary Table A.4 and Table A.5). The upland switchgrass yields ranged from 2.1 to 27.5 Mg/ha with an average of 9.1 Mg/ha, and the *Miscanthus* yields ranged from 3.5 to 48.5 Mg/ha with an average of 28.0 Mg/ha. Simulated switchgrass yield (ranging from 2.6 to 11.48 Mg/ha with the average of 8.4 Mg/ha) was a little lower than the measurements. However, simulated *Miscanthus* yield (ranging from 1.9 to 43.71 Mg/ha with an average of 10.0 Mg/ha) was much lower than the average yield obtained from the field experiments. The comparison of the yield with its variation indicated that the model represented the responses of the crop growth to a range of growing conditions. An analysis of simulated switchgrass and *Miscanthus* yield distribution across marginal land plots indicated that switchgrass mostly ranged from 7 to 10 Mg/ha, while *Miscanthus* yield ranged from 8 to 14 Mg/ha (Feng, 2013). The generally lower simulated *Miscanthus* yield could thus be attributed to poor marginal land quality. This result indicated that there would be some opportunity for yield increase on marginal land, such as using better management practices. Combined with the indication that marginal land may not all suitable for producing these perennial crops, the biofuel production estimated in this study contains some uncertainties and required further researches for better estimation.

3.4 Impacts on hydrology

Water yield (WYLD) simulated with the baseline and biomass production scenarios were compared (Table 2). The results showed that biomass production generally reduced water yield of the watershed by 13.4% (MF scenario) to 36.3% (SGLCC scenario). The hydrologic simulation results were further investigated to identify hydrologic processes that led to the water yield reduction. Changes in WYLD, surface runoff (Q), ET, Return subsurface flow (RSSF), quick return flow (QRF), and flow from tile drainage (QDR) simulated with the scenarios were compared. It should be noted that tile drains were installed only in corn/soybean land that has poor drained soils (Supplementary Table A1). Figure 4A shows that ET is the most sensitive to the scenarios, implying the reduction of WYLD could be attributed to increased ET and subsequent decrease in RSSF. ET was greater under the biomass production scenarios than the baseline scenario. It has been reported that simulated ET for switchgrass and *Miscanthus* tended to be greater than that of corn/soybean due to greater leaf area index (LAI) and prolonged growing season (Hickman et al., 2010; Vanloocke et al., 2010; Le et al., 2011; Wu et al., 2012a; Wu et al., 2012b), which was confirmed by field observations made by McIsaac et al. (2010). The increased ET would reduce the soil moisture (SM) content, and then decrease the amount of flow (Q, RSSF, QRF, and QDR), especially subsurface water.

Table 2 Comparison of hydrologic and water quality variables under biomass production scenarios on marginal land scale

	Water Yield (mm)	Soil Erosion (Mg/ha)	N transported by sediment (kg/ha)	N transported by water (kg/ha)	P transported by sediment (kg/ha)	P transported by water (kg/ha)
BGLCC	420a	0.66a	0.79a	14.99a	0.14a	0.000a
SGLCC	317b	0.44b	0.98a	5.72b	0.20a	0.000a
MGLCC	335b	0.03c	0.25b	1.35c	0.07b	0.000a
BCLCC	423a	1.44a	2.73a	81.23a	0.62a	0.031a
SCLCC	333b	0.37b	0.78b	36.48b	0.16b	0.000b
MCLCC	348b	0.02b	0.15b	6.98c	0.04b	0.000b
BB10	458a	0.42a	2.33a	34.50a	0.99a	0.026a
SB10	309b	0.18b	0.92ab	19.90b	0.24b	0.000b
MB10	340b	0.03b	0.24b	4.23c	0.06b	0.000b
BF	395a	0.50a	1.03b	2.26a	0.28a	0.000a
SF	302b	0.36b	1.80a	3.32a	0.58b	0.000a
MF	330b	0.03b	0.33b	1.96b	0.14a	0.000a

- 1 1. Values calculated at marginal land scale values were area weighted average values across
2 marginal land subareas. For example, water yield under BGLCC was the area weighted
3 average values across subareas that were grassland with LCC 3 and 4. This is also the
4 reason why values for variables under baseline scenarios were different.
- 5 2. Different letter after the value indicates significant difference ($p < 0.05$) of values under
6 current land cover type (baseline scenario) and under switchgrass or *Miscanthus*,
7 respectively.
8

Figure 4 Impacts on hydrology (A), nitrogen loss (B), soil erosion and phosphorus loss (C) under biomass production scenarios at marginal land scale. Positive values indicate variable values were increased from baseline scenario. WYLD: water yield, Q: surface runoff; ET: evapotranspiration, RSSF: return subsurface flow; QRF: quick return flow; TN: total nitrogen, QN: soluble nitrogen transported within surface runoff; RSFN: soluble nitrogen transported within return subsurface flow, QRFN: soluble nitrogen transported within quick return flow; QDRN: soluble nitrogen transported within flow from tile drainage; YN: nitrogen transported with sediment; SE: Soil erosion; QP: soluble Phosphorus transported within surface runoff; YP: Phosphorus transported with sediment

Monthly ET, LAI, and SM simulated for corn/soybean, grassland, and forest land on one subarea were compared with those of switchgrass and *Miscanthus* (Supplementary Figure B.1 and B.2). ET of switchgrass and *Miscanthus* was higher than from corn/soybean and grassland, mainly during the growing season (from May to November) (Supplementary Figure B. 1AB). Transpiration that occurs through leaf stomata was the major part of ET during the growing season, and higher transpiration rates could be due to the higher LAI during this period (Supplementary Figure B.1CD). Similar ET was simulated for both switchgrass and *Miscanthus*, even though LAI of *Miscanthus* was higher than switchgrass. This could be due to the limitation of SM availability. SM was low when switchgrass and *Miscanthus* were growing, as shown in Supplementary Figure B.1EF. During the non-growing season (from December to April), ET from *Miscanthus* was lower than from switchgrass, corn/soybean and grassland. Evaporation from the soil surface was the major component of ET after biomass harvest in October, and thus low evaporation rate could be attributed to *Miscanthus* residues and low soil moisture in *Miscanthus* plots. In the forest land use, trees were assumed to be planted at the beginning of the simulation period (1995). During the first few years of tree establishment (until 2002), LAI of trees was lower than those of switchgrass and *Miscanthus* (Supplementary Figure B.2B). Until 2002, the LAI developed to a point that could cause similar amounts of ET with switchgrass and *Miscanthus*. ET under established forest and under switchgrass and *Miscanthus* was also constrained by the amount of available SM (Supplementary Figure B.2C).

WYLD simulated with the scenarios were compared at a watershed scale (Table 3). The reduction of WYLD was less than 5% at the watershed scale and not statistically significant ($p>0.05$) because the area of the marginal land constitutes only 22% of the total land in the watershed. As Vanlooke *et al.* (2010) reported, significant impacts on water yield might not happen if the *Miscanthus* coverage was less than 25% of dry regions or 50% of the Midwest area.

Table 3 Comparison of hydrologic and water quality variables under biomass production scenarios at a watershed scale

	Water Yield (mm)	Soil Erosion (Mg/ha)	N transported by sediment (kg/ha)	N transported by water (kg/ha)	P transported by sediment (kg/ha)	P transported by water (kg/ha)
B	408	0.85	2.18	22.89	0.78	0.025
SGLCC	393	0.83	2.06	22.03	0.66	0.021
MGLCC	394	0.80	1.98	21.64	0.65	0.021
SCLCC	401	0.75	2.00	21.87	0.73	0.022
MCLCC	402	0.71	1.93	18.96	0.72	0.022
SB10	408	0.85	2.18	22.76	0.78	0.025
MB10	408	0.85	2.18	22.75	0.78	0.025
SF	394	0.82	2.19	22.89	0.78	0.025
MF	394	0.81	2.18	22.89	0.78	0.025

1. Values calculated at a watershed scale are area weighted average values across all subareas in the study watershed.

2. Values were all statistically insignificant ($p>0.05$) under current land cover type (baseline scenario) and under scenarios of producing switchgrass or *Miscanthus*.

3.5 Impacts on soil erosion

Soil erosion was generally reduced with the biomass production scenarios compared to the baseline at statistically significant levels ($p<0.05$) (Table 2). The reduction ranged from 27% for scenario SF to 98% for scenario MCLCC. Especially under the *Miscanthus* scenarios, soil erosion was reduced by more than 90%. Field observations of soil erosion under switchgrass and *Miscanthus* are very limited. Current published results are generally simulation results based on Universal Soil Erosion Loss (USLE) equation techniques. In this study, soil erosion was calculated using the MUSLE equation. The impacts on soil erosion resulted from the combined effects on erosivity (R) factor and Crop management factor (C factor). The Q was reduced under the switchgrass and *Miscanthus* scenarios with type 1 and type 2 marginal land but slightly increased with type 3 marginal land. R factor has a positive relationship with Q. As to the C factor, the values under switchgrass and *Miscanthus* were generally lower than original land cover types (Supplementary Figure B.3BDF). On type 3 marginal land, soil erosion was increased under switchgrass probably because of the increase of Q, even though C factor for switchgrass was lower than for forest during the growing season (Supplementary Figure B.3F).

In the APEX model, the C factor is a function of amount of residue, crop height, biomass and surface roughness. An average C factor estimated by the model for *Miscanthus* was 0.0005 and for switchgrass was 0.04 (Supplementary Figures B.3B, D and F). The C factor used by other modelling studies for these two perennial crops are similar to these values (Thomas et al., 2014). Average C factor values calculated by Thomas *et al.* (2014) using the RUSLE2 model ranged from 0.0007 to 0.0011 for established *Miscanthus* and ranged from 0.011 to 0.016 for established switchgrass. Dabney *et al.* (2012, 2014) improved the simulation of perennial crop growth processes in RUSLE2. The improved model provided similar C factor values (Personal communication with Dr. Seth Dabney). In addition, field observations using *Miscanthus* as hedge located within row crops reported that established *Miscanthus* reduced sediment losses by 69% to 84% (Dabney et al., 2009). Similarly, the capability to trap sediment losses by switchgrass used as hedges in row crops fields ranged from 29% to 62% (Meyer et al., 1995). However, further detailed investigations on the C factors and erosion rates for these perennial grasses are required to validate simulation results.

Growing perennial grasses in marginal land reduced sediment loading at the watershed scale. The watershed soil erosion reduction from different marginal land scenarios ranged from 2% (for SGLCC) to 16% (for MCLCC). These changes were environmentally significant. However, these changes were not statistically significant, probably because of the high inter-annual variability of the soil erosion rate.

3.6 Impacts on nutrient loss

Nitrogen (N) and phosphorus (P) losses simulated with the scenarios are compared in Table 2. Losses of N and P through both water and sediment were reduced under the biomass production scenarios that include corn and soybean marginal land (SCLCC, MCLCC, SB10, MB10). However, losses of N and P through both water and sediment were increased under the switchgrass scenarios (SGLCC and SF) but decreased under the *Miscanthus* scenarios (MGLCC and MF) on grassland and forest marginal land compared with baseline scenario.

The mechanisms for nutrient loss were further investigated by analyzing the changes of N and P losses through different hydrologic processes and sediment (Figure 4B and 4C). The simulated values for N losses were comparable to field-observed data (McIsaac et al., 2010). The results indicated that TN loss reduction under almost all scenarios was mainly due to the reduction of N transported by underground water flow (RSFN or QDRN). Total P loss reduction

under almost all scenarios was mainly due to the reduction of P transported with sediment. The changes of N and P losses followed the trend in hydrologic processes and sediment. These results indicated that the reduction of N and P losses were the results of combined effects from changes of fertilization rates and the amount of transport medium. The differences in N and P loss trends under different scenarios were due to variations in soil, topography, and types of original land cover (Demissie et al., 2012). Differences in plant uptake may be another reason for changes in nutrient loss from fields. Nelson et al. (2006) reported that nutrient loss under corn/soybean rotation could be reduced by 65.3% with unfertilized switchgrass.

Reduction in N loss with *Miscanthus* was greater compared to switchgrass (Figure 4). The reason was investigated by analyzing monthly N losses from one subarea (Supplementary Figure B.4). QDRN was the major part of N loss for corn and soybean, and RSFN was the major part of N loss for grassland and forest. QDRN and RSFN for *Miscanthus* were lower than switchgrass mainly during the non-growing season, which was the time between harvesting and fertilizer application the next year. The two perennial grasses were harvested on Oct 29 (Supplementary Table A.3). The amount of QDRN and RSFN under switchgrass increased at a higher rate than under *Miscanthus* before the crops were harvested. A similar trend was reported in another study using model simulation by the SWAT model with the same fertilization rate for switchgrass and *Miscanthus* (Cibin and Chaubey, 2013). However, McIsaac et al. (2010) did not find significant differences in N loss for *Miscanthus* and switchgrass during the establishment stage.

Comparisons among N and P losses under various scenarios at the watershed scale are presented in Table 3. At watershed scale, reduction of N transported by sediment ranged from 6% (for SGLCC) to 11% (for MCLCC), and reduction of N transported by water ranged from 0.6% (for MB10) to 17% (for MCLCC). As for P, reduction of P transported by sediment ranged from 6% (for SCLCC) to 17% (for MCLCC), and reduction of P transported by water ranged from 12% (for SCLCC) to 16% (for MGLCC). The impacts were also environmental significant as the reduction of soil erosion. However, these changes were not statistically significant, probably because of the high inter-annual variability of these nutrient variables.

4. Conclusions

Three types of marginal land were defined and delineated for the St. Joseph River watershed. The marginal lands considered in this study included (1) type 1: cropland and grassland that are

1 in LCC 3 and 4 soils, (2) type 2: land located in 10 m buffers along major streams, and (3) type
2 3: forest land located in 50 m buffers around corn and soybean land. The potential biofuel
3 production that can be obtained by growing switchgrass and *Miscanthus* on marginal land were
4 estimated, and its impacts on hydrologic processes and water quality were evaluated using the
5 APEX model. The total area of the three types of marginal land was 610 km², about 21.7% of the
6 total area of St. Joseph River watershed. The major part of marginal land area for the watershed
7 came from type 1 and type 3 marginal lands. About 161 to 207 million liter of bioethanol can be
8 produced from growing switchgrass and *Miscanthus* on marginal land in the St. Joseph River
9 watershed.

10 Water yield was reduced by from 13% to 36% under various biomass production scenarios due
11 to higher ET from switchgrass and *Miscanthus*, compared with water yield from baseline
12 scenario. Higher evapotranspiration decreased the availability of soil moisture and thus
13 subsurface flow (RSSF and QDR). Soil erosion would also be reduced (by from 13.4% to 36.3%)
14 due to better protection provided by switchgrass and *Miscanthus*. N and P loss would be reduced
15 under biomass production scenarios that included corn and soybean land. Under biomass
16 production scenarios that included grassland and forest, losses of N and P increased under
17 switchgrass, but reduced under *Miscanthus*. These changes were statistically and
18 environmentally significant at marginal land scale. At watershed scales, they were
19 environmentally significant, even though not statistically significant. The results indicated that
20 utilizing marginal land for biofuel production could influence hydrologic processes by reducing
21 WYLD and bring some benefits to water quality.

22
23 **5. Acknowledgements** – This study was funded by the US Department of Energy (Award
24 No. DE-EE0004396) and USDA-NIFA (Award No. 416-17-01G). Constructive
25 comments provided by three anonymous reviewers and Dr. Dan Ames (Associate Editor)
26 greatly improved earlier versions of this manuscript.

6. Appendices A. Supplementary Tables

Supplementary Table A1. List of parameters specified in input table for each subarea

File	Parameter	Description	Source/Value
APEXRUN	ASTN	Run number	Land plot ID
	ISIT	Site number	Land plot ID
	ISUB	Subarea ID	Land plot ID
	NBYR	Simulation duration	15
	IYR	Beginning year	1995
	IMO	Beginning month	1
	IDA	Beginning day	1
	IPD	Output option	Annual output
	IET	PET ¹ equation	Penman-Monteith
	INFL	Runoff equation	Green & Ampt method
APEXCONT	DRV	Water erosion equation	MUSLE
.SIT	One file for each field		
	XLOG	Longitude	Land plot Map
	YLAT	Latitude	Land plot Map
	ELEV	Elevation	DEM
SITECOM	One file contains list of all sites (fields).		
.SUB	One for each field		
	SNUM	Subarea ID	Land plot ID
	Title	Description	Land plot ID
	WSA	Watershed area	Land plot map
	SLP	average upland slope	DEM
	SPLG	Average upland slope length	DEM
	YCT	Longitude	Land plot map
	XCT	Latitude	Land plot map
	INPS	Soil number	Soil list
	IOPS	Operation schedule	From land use list
	IUNS	land use number for CN	CDL2010
	CHL	Distance from outlet to the most distand pont on watershed	DEM
	CHS	Channel slope	DEM
	CHN	Manning's N for channel.	APEX User manual
	RCHL	Reach channel length	Equal to CHL
	UPN	Manning's N for upland	APEX User manual
	DRT	Time requirement for drainage system to end plant stress in days	0.5 day
	IDR	Drainage code	1000 mm
SUBACOM	One file contains list of all subareas (fields).		

.SOL	One for each field, data from SSURGO, 444 file for 444 soil types	
.OPS	One for each field; OPS files for corn/soybean rotation, switchgrass and <i>Miscanthus</i> were provided in SI Table A2. For other land cover types, the default OPS file from ArcAPEX database were extracted and used in the simulation.	
CROPCOM	Parameters for switchgrass and <i>Miscanthus</i> were modified according to values developed by Trybula et al. (2013) for SWAT model.	
.WP1	Monthly weather file	APEX default database
.DLY	Daily weather input	NCDC stations around St. Joseph
.WIN	Wind data input	APEX default database

DRT and IDR were parameters controlling tile drainage in each subarea. In this study, tile drainage was installed only on corn/soybean land that had soils with somewhat poorly-, poorly-, and very poorly drainage properties according to SSURGO dataset.

Supplementary Table A2 Management practices for corn/soybean rotation, switchgrass and *Miscanthus*

Plant	Management		
Corn/ soybean rotation	For corn year		
	Date	Practices	Detail
	April 22	N application	Anhydrous ammonia 212 kg/ha
	April 22	P Fertilizer	P ₂ O ₅ , 67 kg/ha
	April 22	Pesticide	Atrazine, 2.2 kg/ha
	May 6	Tillage	Offset disk plow, 100 mm, 60 % mixing.
	May 6	Plant	
	Oct 14	Harvest	
	For soybean year		
	May 10	P Fertilizer	P ₂ O ₅ , 45 kg/ha
	May 24	Plant with no till	
	Oct 7	Harvest	
	Nov 1	Tillage	Chisel plow (30% mixing to 150mm)
Switchgrass/ <i>Miscanthus</i>	First year		
	May 15	Planting	
	May 22	N Fertilizer	Urea 61 kg/ha (28 kgN/ha)
	Second to 8 th year		

May 22	N Fertilizer	Urea 61 kg/ha (28 kgN/ha)
Oct 29	Harvest	

1 Tips:

1. This management practices include two year corn-soybean rotation. Planting and harvesting dates were determined based on the 50% area planting/harvesting dates. Fertilizer application rate were developed based on information provided by Tri state recommendations (Vitosh et al., 1995) for corn and soybeans. Pesticide estimation was estimated using the maximum label rate for atrazine application. These information were obtained from (Kalcic et al., 2013).
2. Management practices for switchgrass and *Miscanthus* were developed based on the practices used in Water Quality Field Station, Purdue University, West Lafayette, IN, US. It is assumed that the two perennial crops could provide steady yield for 8 continuous years and need to be replanted at the 9th year.

Supplementary Table A3 Parameters used in flow and total nitrogen calibration

Parameters	Description	Recommended Ranges	Values used in calibration	Default value
Parameters for flow calibration				
IET	PET equation code	0 to 4	4	0
INFL	Runoff equation methodology	0 to 4	1	0
IDR	Drainage depth in mm	0 to 2500 mm	1000	0
DRT	Time for drainage system to end plant stress in days	0 to 365 days	0.5 day	0
RFTO	Ground water resident time in days	0 to 365	1.6 days	0
RFPO	Return flow portion	0 to 1	0.95	0.5
SATO	Saturated Conductivity adjustment factor	0.01 to 10	0.70	1.0
P12	Soil evaporation coefficient	1.5 to 2.5	2.5	2.5
P17	Evaporation plant cover factor	0.00 to 0.5	0.05	0
Parameters for total nitrogen calibration				
P7	Nitrogen fixation coefficient	0-1	0.1	0.9
P29	Biological mixing efficiency	0.1-0.5	0.45	0.2
P72	Volatilization/nitrification partitioning coefficient	0.05-0.5	0.1	0.4
P74	Partitions nitrogen flow from groundwater	0-20	0.009	0.01

Supplementary Table A4 Measured yield of switchgrass at different field experimental sites across the U.S. collected from literature.

ID	County	State	Average yield (Mg/ha)	Literature
1	Dickinson	North Dakota	4.6	Berdahl et al., 2005
2	Mandan	North Dakota	6.9	
3	Arlington	Wisconsin	11.3	Casler et al., 2007
4	Manhattan	Kansas	7.5	
5	Mead	Nebraska	13.9	Casler and Boe, 2003
6	Stillwater	Oklahoma	11.5	
7	Brookings	South Dakota	4.2	Cassida et al., 2005
8	Spooner	Wisconsin	7.4	
9	Clinton	Louisiana	2.1	Fike et al., 2006;
10	College station	Texas	7.0	
11	Dallas	Texas	5.7	Fuentes and Taliaferro, 2002
12	Hope	Arkansas	9.7	
13	Stephenville	Texas	4.5	Haque, 2009;
14	Arlington	Wisconsin	10.8	
15	Jackson	Tennessee	10.2	Heaton et al., 2008
16	Knoxville	Tennessee	15.8	
17	Morgantown	West Virginia	11.4	Lemus, 2002
18	Orange	Virginia	8.9	
19	Princeton	Kentucky	10.1	Muir et al., 2001
20	Raleigh	North Carolina	8.8	
21	Chickasha	Oklahoma	9.6	Woodson, 2011
22	Haskell	Oklahoma	11.7	
23	Stillwater	Oklahoma	10.9	Sanderson et al., 1999;
24	Dixon Springs	Illinois	8.7	
25	Shabbona	Illinois	8.1	Sanderson et al., 1999;
26	Urbana	Illinois	19.8	
27	Chariton	Iowa	8.5	Sanderson et al., 1999;
28	College station	Texas	6.2	
29	West Lafayette	Indiana	11.3	Sanderson et al., 1999;
30	Beeville	Texas	3.5	
31	Dallas	Texas	8.6	

32	Stephenville	Texas	6.5	1
33	Temple	Texas	5.1	
34	Blacksburg	Virginia	9.5	
35	Milstead	Alabama	9.2	Sladden et al., 1991
36	Chickasha	Oklahoma	16.0	Thomason et al., 2004
37	Perkins	Oklahoma	9.0	
38	Ames	Iowa	9.7	Vogel et al., 2002

Supplementary Table A5 Measured yield of *Miscanthus* at different field experimental sites across the U.S. collected from literature.

ID	County	State	Average yield (Mg/ha)	Literature
1	Shabbona	Illinois	27.75	Heaton et al., 2008
2	Urbana	Illinois	46.73	
3	Dixon Springs	Illinois	48.53	
4	West Lafayette	Indiana	19.81	Patric, 2011
5	Milstead	Alabama	9.17	Sladden et al., 1991
6	Elsberry	Missouri	33.65	Kiniry et al., 2013
7	Columbia	Missouri	21.55	
8	Mt. Vernon	Missouri	13.9	
9	Stillwater	Oklahoma	3.5	
10	Fayetteville	Arizona	10.45	
11	Booneville	Arizona	4.5	
12	Nacogdoches	Texas	3.95	
13	Temple	Texas	4.2	
14	Kingsville	Texas	5.4	

7. Appendices B. Supplementary Figures

Supplementary Figure B1 Comparison of average monthly evapotranspiration (A and B), leaf area index (C and D) and soil moisture (E and F) from one of corn/soybean (A, C and E) and pasture (B, D and F) fields (or one subarea in APEX), respectively. Corn/soybean rotation and range are representative land cover types in type 1 and type 2 marginal land.

Supplementary Figure B2 Comparison of average monthly values of Evapotranspiration (A), Leaf Area Index (B) and Soil moisture (C) from one of forest fields (or one subarea in APEX). Forest is the representative land cover type for type 3 marginal land.

Supplementary Figure B3 Comparison of average monthly values of soil erosion (A, C and E) and C factor (B, D and F) from one of corn/soybean (A and B), pasture (C and D), and forest (E and F) fields (or one subarea in APEX), respectively. Corn/soybean, pasture, and forest are the representative land cover types for type1, type 2, and type 3 marginal land, respectively.

Supplementary Figure B4 Comparison of average monthly values of Nitrogen in flow from tile drainage (A) and return subsurface flow (B, C) from one of corn/soybean (A), pasture (B), and forest (C) subarea, respectively. Corn/soybean, pasture, and forest are the representative land cover types for type1, type 2, and type 3 marginal land, respectively.

8. References

- Bonin, C.L., Lal, R., 2014. Aboveground productivity and soil carbon storage of biofuel crops in Ohio. *Global Change Biology Bioenergy* 6(1) 67-75, doi: 10.1111/gcbb.12041.
- Cai, X., Zhang, X., Wang, D., 2010. Land availability for biofuel production. *Environmental Science & Technology* 45(1) 334-339, doi: 10.1021/es103338e.
- Campbell, J.E., Lobell, D.B., Genova, R.C., Field, C.B., 2008. The global potential of bioenergy on abandoned agriculture lands. *Environmental Science & Technology* 42(15) 5791-5794, doi: 10.1021/es800052w
- Cibin, R., Chaubey, I., Engel, B., 2012. Simulated watershed scale impacts of corn stover removal for biofuel on hydrology and water quality. *Hydrological Processes* 26(11) 1629-1641, doi: 10.1002/hyp.8280
- Cibin, R., Chaubey, I., 2015. A computationally efficient approach for watershed scale spatial optimization. *Environmental Modelling & Software* 66(0) 1-11, doi: <http://dx.doi.org/10.1016/j.envsoft.2014.12.014>
- Costello, C., Griffin, W.M., Landis, A.E., Matthews, H.S., 2009. Impact of biofuel crop production on the formation of hypoxia in the Gulf of Mexico. *Environmental Science & Technology* 43(20) 7985-7991, doi: 10.1021/es9011433.
- Dabney, S.M., McGregor, K.C., Wilson, G.V., Cullum, R.F., 2009. How Management of Grass Hedges Affects their Erosion Reduction Potential. *Soil Science Society of America Journal* 73, 241. doi:10.2136/sssaj2007.0434
- Dabney, S.M., Yoder, D.C., 2012. Improved descriptions of herbaceous perennial growth and residue creation for RUSLE2. *Agronomy Journal* 104(3) 771-784, doi: 10.2134/agronj2011.0356
- Dabney, S.M., Yoder, D.C., Ferruzzi, G.G., 2014. Forage harvest representation in RUSLE2. *Agronomy Journal* 106(1) 151-167, doi: 10.2134/agronj2013.0059
- 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 & Technology* 46(16) 9174-9182, doi: 10.1021/es300769k
- Downing, M., Eaton, L.M., Graham, R.L., Langholtz, M.H., Perlack, R.D., Turhollow Jr, A.F., Stokes, B., Brandt, C.C., 2011. U.S. Billion-ton update: biomass supply for a bioenergy and bioproducts industry. Retrieved from http://www1.eere.energy.gov/bioenergy/pdfs/billion_ton_update.pdf

1 Elobeid, A., Tokgoz, S., Dodder, R., Johnson, T., Kaplan, O., Kurkalova, L., Secchi, S., 2013. Integration
2 of agricultural and energy system models for biofuel assessment. *Environmental Modelling & Software*
3 48 1-16, doi: 10.1016/j.envsoft.2013.05.007

4 Engel, B., Chaubey, I., Thomas, M., Saraswat, D., Murphy, P., Bhaduri, B., 2010. Biofuels and water
5 quality: challenges and opportunities for simulation modeling. *Biofuels* 1(3) 463-477, doi:
6 <http://dx.doi.org/10.4155/BFS.10.17>.

7 Feng, Q., 2013. Biomass production and hydrological/water quality impacts of perennial crop production
8 on marginal land. Retrieved from ProQuest Dissertations and Theses. (Accession Order No.
9 AAI1553513)

10 Gassman, P.W., Williams, J.R., Wang, X., Saleh, A., Osei, E., Hauck, L., Izaurrealde, R.C., Flowers, J.,
11 2010. The Agricultural Policy/Environmental Extender (Apex) Model: An emerging tool for landscape
12 and watershed environmental analyses. *Transactions of the ASABE*, 53(3):711-740, doi:
13 10.13031/2013.30078.

14 Gelfand, I., Sahajpal, R., Zhang, X., Izaurrealde, R.C., Gross, K.L., Robertson, G.P., 2013. Sustainable
15 bioenergy production from marginal lands in the US Midwest. *Nature* 493(7433) 514-517,
16 doi:10.1038/nature11811.

17 Gopalakrishnan, G., Negri, M.C., Wang, M., Wu, M., Snyder, S.W., Lafreniere, L., 2009. Biofuels, land,
18 and water: a systems approach to sustainability. *Environmental Science & Technology* 43(15) 6094-6100,
19 doi: 10.1021/es900801u.

20 Gopalakrishnan, G., Cristina Negri, M., Snyder, S.W., 2011. A novel framework to classify marginal land
21 for sustainable biomass feedstock production. *Journal of Environ Quality* 40(5) 1593-1600, doi:
22 10.2134/jeq2010.0539.

23 Hamdar, B., 1999. An efficiency approach to managing Mississippi's marginal land based on the
24 conservation reserve program (CRP). *Resources Conservation and Recycling* 26(1) 15-24.

25 Heaton, E., Voigt, T., Long, S.P., 2004. A quantitative review comparing the yields of two candidate C-4
26 perennial biomass crops in relation to nitrogen, temperature and water. *Biomass & Bioenergy* 27(1) 21-
27 30, doi:10.1016/j.biombioe.2003.10.005

28 Heaton, E.A., Dohleman, F.G., Long, S.P., 2008. Meeting US biofuel goals with less land: the potential of
29 *Miscanthus*. *Global Change Biology* 14(9) 2000-2014, doi: 10.1111/j.1365-2486.2008.01662.x

1 Hickman, G.C., Vanloocke, A., Dohleman, F.G., Bernacchi, C.J., 2010. A comparison of canopy
2 evapotranspiration for maize and two perennial grasses identified as potential bioenergy crops. *Global*
3 *Change Biology Bioenergy* 2(4) 157-168, doi: 10.1111/j.1757-1707.2010.01050.x

4 Kang, S., Post, W., Wang, D., Nichols, J., Bandaru, V., West, T., 2013a. Hierarchical marginal land
5 assessment for land use planning. *Land Use Policy* 30(1) 106-113, doi:10.1016/j.landusepol.2012.03.002.

6 Kang, S.J., Post, W.M., Nichols, J.A., Wang, D., West, T.O., Bandaru, V., Izaurralde, R.C., 2013b.
7 Marginal lands: concept, assessment and management. *Land Use Policy* 5(5) 129-139, doi:
8 10.5539/jas.v5n5p129.

9 Le, P.V., Kumar, P., Drewry, D.T., 2011. Implications for the hydrologic cycle under climate change due
10 to the expansion of bioenergy crops in the Midwestern United States. *Proceedings of the National*
11 *Academy of Sciences of the United States of America* 108(37) 15085-15090, doi:
12 10.1073/pnas.1107177108

13 Liu, T.T., McConkey, B.G., Ma, Z.Y., Liu, Z.G., Li, X., Cheng, L.L., 2011. Strengths, weaknessness,
14 opportunities and threats analysis of bioenergy production on marginal land. 2010 International
15 Conference on Energy, Environment and Development (Iceed2010) 5(0) 2378-2386,
16 doi:10.1016/j.egypro.2011.03.409.

17 Love, B.J., Nejadhashemi, A.P., 2011. Water quality impact assessment of large-scale biofuel crops
18 expansion in agricultural regions of Michigan. *Biomass & Bioenergy* 35(5) 2200-2216,
19 doi:10.1016/j.biombioe.2011.02.041

20 McIsaac, G.F., David, M.B., Mitchell, C.A., 2010. *Miscanthus* and switchgrass production in central
21 Illinois: impacts on hydrology and inorganic nitrogen leaching. *Journal of Environmental Quality* 39(5)
22 1790-1799, doi:10.2134/jeq2009.0497

23 McLaughlin, M.R., Fairbrother, T.E., Rowe, D.E., 2004. Nutrient uptake by warm-season perennial
24 grasses in a swine effluent spray field. *Agronomy Journal* 96(2) 484-493, doi:10.2134/agronj2004.4840

25 Meyer, L.D., Dabney, S.M., Harmon, W.C., 1995. Sediment-trapping effectiveness of stiff-grass hedges.
26 *Transactions of the ASAE* 38, 809–815.

27 Monteith, J.L., 1965. Evaporation and environment. *Symp. Soc. Exp. Biol.* 19, 205–234.

28 Moriasi, D.N., Arnold, J.G., van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model
29 evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of*
30 *the ASABE* 50(3) 885-900.

1 Nelson, R.G., Ascough, J.C., 2nd, Langemeier, M.R., 2006. Environmental and economic analysis of
2 switchgrass production for water quality improvement in northeast Kansas. *Journal of Environmental*
3 *Management* 79(4) 336-347, doi:10.1016/j.jenvman.2005.07.013.

4 Ng, T.L., Eheart, J.W., Cai, X., Miguez, F., 2010. Modeling *Miscanthus* in the soil and water assessment
5 tool (SWAT) to simulate its water quality effects as a bioenergy crop. *Environmental Science &*
6 *Technology* 44(18) 7138-7144.

7 Pimentel, D., Marklein, A., Toth, M.A., Karpoff, M.N., Paul, G.S., McCormack, R., Kyriazis, J., Krueger,
8 T., 2009. Food versus biofuels: environmental and economic costs. *Human Ecology* 37(1) 1-12, DOI:
9 10.1007/s10745-009-9215-8

10 Renewable Fuels Association. Monthly U.S. fuel ethanol production/demand.
11 <http://ethanolrfa.org/pages/monthly-fuel-ethanol-production-demand>, Accessed on Feb 10, 2015

12 Robertson, G.P., Dale, V.H., Doering, O.C., Hamburg, S.P., Melillo, J.M., Wander, M.M., Parton, W.J.,
13 Adler, P.R., Barney, J.N., Cruse, R.M., Duke, C.S., Fearnside, P.M., Follett, R.F., Gibbs, H.K.,
14 Goldemberg, J., Mladenoff, D.J., Ojima, D., Palmer, M.W., Sharpley, A., Wallace, L., Weathers, K.C.,
15 Wiens, J.A., Wilhelm, W.W., 2008. Agriculture: sustainable biofuels redux. *Science* 322(5898) 49-50,
16 DOI: 10.1126/science.1161525.

17 Tang, Y., Xie, J.S., Geng, S., 2010. Marginal land-based biomass energy production in China. *Journal of*
18 *Integrative Plant Biology* 52(1) 112-121, doi: 10.1111/j.1744-7909.2010.00903.x.

19 Thomas, M. , Ahiablame, L. , Engel, B. and Chaubey, I. 2014. Modeling water quality impacts of
20 growing corn, switchgrass, and *Miscanthus* on marginal soils. *Journal of Water Resource and Protection*,
21 6, 1352-1368. doi: 10.4236/jwarp.2014.614125.

22 Tilman, D., Hill, J., Lehman, C., 2006. Carbon-negative biofuels from low-input high-diversity grassland
23 biomass. *Science* 314(5805) 1598-1600.

24 Trybula, E.M., Cibin, R., Burks, J.L., Chaubey, I., Brouder, S.M., Volenec, J.J., 2014. Perennial
25 rhizomatous grasses as bioenergy feedstock in SWAT: parameter development and model improvement.
26 *Global Change Biology Bioenergy*, doi: 10.1111/gcbb.12210

27 U.S. Department of Agriculture, 2010. A USDA regional roadmap to meeting the biofuels goals of the
28 renewable fuels standard by 2022. Retrieved from:
29 http://www.usda.gov/documents/USDA_Biofuels_Report_6232010.pdf

- 1 U.S. Environmental Protection Agency, United States, 2010. Changes to renewable fuel standard program
- 2 regulation of fuels and fuel activities final rule. Retrieved from: [http://www.gpo.gov/fdsys/pkg/FR-2010-](http://www.gpo.gov/fdsys/pkg/FR-2010-03-26/pdf/2010-3851.pdf)
- 3 [03-26/pdf/2010-3851.pdf](http://www.gpo.gov/fdsys/pkg/FR-2010-03-26/pdf/2010-3851.pdf)
- 4 U.S. Government Information, 2014. Agricultural Act of 2014. Retrieved from:
- 5 <https://www.congress.gov/113/bills/hr2642/BILLS-113hr2642enr.pdf>
- 6 Vanloocke, A., Bernacchi, C.J., Twine, T.E., 2010. The impacts of *Miscanthus*×*giganteus* production on
- 7 the Midwest US hydrologic cycle. *Global Change Biology Bioenergy* 2(4) 180-191, doi: 10.1111/j.1757-
- 8 1707.2010.01053.x
- 9 Wiegmann, K., Hennenberg, K.J., Fritsche, U.R., 2008. Degraded land and sustainable bioenergy
- 10 feedstock production, Issue Paper-Joint International Workshop on high nature value criteria and potential
- 11 for sustainable use of degraded lands, Paris.
- 12 Williams, J.R., 1975. Sediment yield prediction with universal equation using runoff energy factor. U.S.
- 13 Department of Agriculture, Agricultural Research Service, ARS-S-40,
- 14 Williams, J.R. & Izaurralde R.C., 2006. The APEX model. In V. P. Singh & D.K. Frevert (Eds.),
- 15 *Watershed models* (pp 437 – 482). Boca Raton, Fla: CRC Press
- 16 Williams, J.R., Izaurralde, R.C., Steglish, E.M., 2012. Agricultural policy/environmental eXtender
- 17 model: Theoretical Document. Retrieved from: <http://apex.tamu.edu/>
- 18 Woodson, P.W., 2011. The impact of phosphorus and potassium fertility regimes on switchgrass yield
- 19 and biomass composition. Retrieved from ProQuest Dissertations and Theses. (Accession Order No.
- 20 AAI1502157)
- 21 Wu, M., Demissie, Y., Yan, E., 2012a. Simulated impact of future biofuel production on water quality
- 22 and water cycle dynamics in the Upper Mississippi river basin. *Biomass & Bioenergy* 41(0) 44-56,
- 23 doi:10.1016/j.biombioe.2012.01.030
- 24 Wu, Y.P., Liu, S.G., Li, Z.P., 2012b. Identifying potential areas for biofuel production and evaluating the
- 25 environmental effects: a case study of the James River Basin in the Midwestern United States. *Global*
- 26 *Change Biology Bioenergy* 4(6) 875-888, doi: 10.1111/j.1757-1707.2012.01164.x
- 27 Zub, H.W., Brancourt-Hulmel, M., 2010. Agronomic and physiological performances of different species
- 28 of *Miscanthus*, a major energy crop. A review. *Agronomy for Sustainable Development* 30(2) 201-214,
- 29 doi: 10.1051/agro/2009034

30 **References in Supplementary Table A4&5:**

1 Berdahl, J.D., Frank, A.B., Krupinsky, J.M., Carr, P.M., Hanson, J.D., Johnson, H.A., 2005. Biomass
2 yield, phenology, and survival of diverse switchgrass cultivars and experimental strains in western North
3 Dakota. *Agronomy Journal* 97(2) 549-555.

4 Casler, M.D., Boe, A.R., 2003. Cultivar X environment interactions in switchgrass. *Crop Science* 43(6)
5 2226-2233.

6 Casler, M.D., Vogel, K.P., Taliaferro, C.M., Ehlke, N.J., Berdahl, J.D., Brummer, E.C., Kallenbach, R.L.,
7 West, C.P., Mitchell, R.B., 2007. Latitudinal and longitudinal adaptation of switchgrass populations. *Crop*
8 *Science* 47(6) 2249-2260.

9 Cassida, K.A., Muir, J.P., Hussey, M.A., Read, J.C., Venuto, B.C., Ocumpaugh, W.R., 2005. Biomass
10 yield and stand characteristics of switchgrass in south central U.S. environments. *Crop Science* 45(2) 673.

11 Fike, J.H., Parrish, D.J., Wolf, D.D., Balasko, J.A., Green, J.T., Rasnake, M., Reynolds, J.H., 2006. Long-
12 term yield potential of switchgrass-for-biofuel systems. *Biomass & Bioenergy* 30(3) 198-206.

13 Fuentes, R.G., Taliaferro, C.M., 2002. Biomass yield stability of switchgrass cultivars. ASHS Press,
14 Alexandria,.

15 Haque, M., Epplin, F.M., Taliaferro, C.M., 2009. Nitrogen and harvest frequency effect on yield and cost
16 for four perennial grasses. *Agronomy Journal* 101(6) 1463-1469.

17 Heber Green, W., Ampt, G., 1911. Studies on soil physics. *The Journal of Agricultural Science* 4(01) 1-
18 24.

19 Heaton, E.A., Dohleman, F.G., Long, S.P., 2008. Meeting US biofuel goals with less land: the potential of
20 *Miscanthus*. *Global Change Biology* 14(9) 2000-2014.

21 Kalcic, M., Prokopy, L., Frankenberger, J., Chaubey, I., 2014. An in-depth examination of farmers'
22 perceptions of targeting conservation practices. *Environmental Management* 54(4) 795-813, doi:
23 10.1007/s00267-014-0342-7

24 Kiniry, J.R., Anderson, L.C., Johnson, M.V.V., Behrman, K.D., Brakie, M., Burner, D., Cordsiemon,
25 R.L., Fay, P.A., Fritschi, F.B., Houx, J.H., III, Hawkes, C., Juenger, T., Kaiser, J., Keitt, T.H., Lloyd-
26 Reilley, J., Maher, S., Raper, R., Scott, A., Shadow, A., West, C., Wu, Y., Zibilske, L., 2013. Perennial
27 biomass grasses and the Mason–Dixon Line: comparative productivity across latitudes in the Southern
28 Great Plains. *Bioenergy Research* 6(1) 276-291.

29 Lemus, R., Brummer, E.C., Moore, K.J., Molstad, N.E., Burras, C.L., Barker, M.F., 2002. Biomass yield
30 and quality of 20 switchgrass populations in southern Iowa, USA. *Biomass & Bioenergy* 23(6) 433-442.

- 1 Muir, J.P., Sanderson, M.A., Ocumpaugh, W.R., Jones, R.M., Reed, R.L., 2001. Biomass production of
2 'Alamo' switchgrass in response to nitrogen, phosphorus, and row spacing. *Agronomy Journal* 93(4) 896-
3 901.
- 4 Sanderson, M.A., Reed, R.L., Ocumpaugh, W.R., Hussey, M.A., Van Esbroeck, G., Read, J.C., Tischler,
5 C., Hons, F.M., 1999. Switchgrass cultivars and germplasm for biomass feedstock production in Texas.
6 *Bioresource Technology* 67(3) 209-219.
- 7 Sladden, S.E., Bransby, D.I., Aiken, G.E., 1991. Biomass yield, composition and production costs for 8
8 switchgrass varieties in Alabama. *Biomass & Bioenergy* 1(2) 119-122.
- 9 Thomason, W.E., Raun, W.R., Johnson, G.V., Taliaferro, C.M., Freeman, K.W., Wynn, K.J., Mullen,
10 R.W., 2004. Switchgrass response to harvest frequency and time and rate of applied nitrogen. *Journal of*
11 *Plant Nutrition* 27(7) 1199-1226.
- 12 Trybula, E.M., Cibin, R., Burks, J.L., Chaubey, I., Brouder, S.M., Volenec, J.J., 2014. Perennial
13 rhizomatous grasses as bioenergy feedstock in SWAT: parameter development and model improvement.
14 *Global Change Biology Bioenergy*, doi: 10.1111/gcbb.12210
- 15 Vitosh, M.L., Johnson, J.W., Mengel, D.B., 1995. Tri-State Fertilizer Recommendations for Corn,
16 Soybeans, Wheat and Alfalfa. Bulletin E-2567, Retrieved from:
17 <https://www.extension.purdue.edu/extmedia/AY/AY-9-32.pdf>
- 18 Vogel, K.P., Brejda, J.J., Walters, D.T., Buxton, D.R., 2002. Switchgrass biomass production in the
19 Midwest USA. *Agronomy Journal* 94(3) 413-420.
- 20 Woodson, P.W., 2011. The Impact of phosphorus and potassium fertility regimes on switchgrass yield
21 and biomass composition. Retrieved from ProQuest Dissertations and Theses. (Accession Order No.
22 AAI1502157)