# Marginal land suitability for switchgrass, Miscanthus and hybrid poplar in the Upper Mississippi River Basin (UMRB)

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## Abstract

Marginal lands are recommended as a viable land resource for biofeedstocks production, but their suitability for biofeedstock crops growth are poorly understood. This study assessed the suitability of marginal lands in Upper Mississippi River Basin (UMRB) for three promising biofeedstock crops, switchgrass, *Miscanthus* and hybrid poplar. The land suitability was categorized into 5 suitability classes (not-, poorly-, moderately-, good- and highly-suitable) based on a fuzzy logic based land suitability evaluation procedure. The results showed that 60% of marginal lands in UMRB were moderately to highly suitable for growth of the targeted biofeedstock crops. Predicted bioethanol production from marginal land in the UMRB with consideration of suitability level was two thirds of the production predicted without consideration of suitability level. Our results better constrain the potential of marginal land for biofuel production as well as the importance of land suitability evaluation for policy analysis targeting biofuel development on marginal lands.



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**Keywords:**

switchgrass, *Miscanthus*, hybrid poplar, bioenergy, marginal land suitability, fuzzy logic

## 1. Introduction

In response to climate change and energy crisis, biofuel is considered a partial solution to meet future energy requirements. Many countries including the U.S. have developed ambitious biofuel goals which require producing vast quantities of biomass. Achieving these ambitious biomass production goals is challenging due to the potential competition for agricultural resources already being used to produce food, animal feed, and fiber (Harvey & Pilgrim, 2011). Agricultural land is already under pressures from various sources including the demand for food to feed by the current and projected population, land degradation, urbanization, among others (Harvey & Pilgrim, 2011; Kastner *et al.*, 2012). Consequently, marginal land is proposed for biofuel production to alleviate the potential risk of competing for land currently used for agricultural production of conventional food/feed crops (Gelfand *et al.*, 2013; Cobuloglu & Büyüktahtakın, 2015). For biomass production, marginal land is generally considered as a set aside land and unsuitable for row crop production (Kang *et al.*, 2013a). Marginal land availability estimate to be range from 0.1 to 1 billion ha globally (Kang *et al.*, 2013b). However, the actual conversion of marginal land for biofeedstock production is not straightforward and efforts are needed to quantify the potential economic and environmental impacts on hydrology and water quality processes (Lewis *et al.*, 2014).

Heterogeneous quality of marginal land is one of the difficulties for practically converting marginal land for biomass production. Land could be considered marginal for many reasons including poor soil structure, soil degradation, site abandonment (Campbell *et al.*, 2008; Milbrandt *et al.*, 2014) or environmental contamination (Gopalakrishnan *et al.*, 2011). Lands located along streams and roads are also considered as marginal (Gopalakrishnan *et al.*, 2009; Lu *et al.*, 2009). The quality and productivity of these different types of marginal lands vary considerably. Theoretically, all of these lands could well-suited for biofeedstock crop production, which is the assumption made by previous studies estimating the contribution of marginal land to the US biofuel production (Campbell *et al.*, 2008; Cai *et al.*, 2011). This assumption could not be verified in reality since their heterogeneous qualities result into different suitability for biomass crop growth (Shortall, 2013).

Generally, perennial biomass crops such as switchgrass, *Miscanthus* (*Miscanthus x giganteus*), and hybrid poplar (*Populus deltoides x Populus nigra*) are recommended to be produced on marginal lands (McLaughlin & Adams Kszos, 2005; Heaton *et al.*, 2008; Sannigrahi *et al.*, 2010; Werling *et al.*, 2014). These perennial crops are selected as candidate biofeedstock crops due to their higher biomass yield and relatively low input requirement compared to traditional annual crops (McLaughlin & Adams Kszos, 2005; Heaton *et al.*, 2008). These properties not only are ideal for being candidates of biofeedstock crops, but also could bring positive impacts on environment, ecosystem services and sustainability of marginal land (Kang *et al.*, 2013b). For example, the high biomass production often reduces erosion by providing better surface protection and minimizing runoff (Vaughan *et al.*, 1989; Parrish & Fike, 2005; Feng *et al.*, 2015). These benefits are based on successful establishment and good aboveground growth, which, in turn, depend on quality of land and proper management practices. Even though these perennial crops are considered to be more widely adaptive than annual crops, their production could still be constrained by environmental factors such as climate conditions, slope, soil depth, salinity, and others. Indeed, marginal lands tend to have more of these constraints than does prime farmland. Therefore, evaluating the suitability of marginal land to support proper land use planning for sustaining both biomass production and environment is needed.

Land use suitability evaluation is a procedure determining qualities of a given land type for a desired purpose (Elsheikh *et al.*, 2013). There are two broad classes of methods, which are the computer-assisted overlaying based methods and the multi-criteria decision making-based methods (Malczewski, 2004). These methods have been developed and applied within Geographic

Information System (GIS) frameworks to evaluate land suitability for various land use types including biomass crop production (Malczewski, 2004). The procedure based on fuzzy logic system is among the most popular methods for its ability to deal with evaluation problems involving imprecise and uncertain data (Malczewski, 2004; Joss *et al.*, 2008). For the land suitability evaluation of biofeedstock crops, the fuzzy logic based land suitability assessment procedure is suitable for two reasons: (1) the understanding of growth constraints on biofuel crops are empirical; and (2) even though multiple plot/field years of study data have been collected on biofeedstock crop growth, these crops have not been widely planted like corn (*Zea mays*), soybeans (*Glycine max*) and wheat (*Triticum aestivum*). Understanding growth limitations of these biomass crops currently relies on experts' opinion or limited experimental evidence. Moreover, scaling up inferences from plots/fields to larger area brings uncertainty embedded in the data for large area analysis. For example, soil properties are commonly included in land suitability assessment (Joss *et al.*, 2008; Elsheikh *et al.*, 2013). Soil data are available for the entire continental US (e.g., the Soil Survey Geographic Database or SSURGO). In reality, values in soil properties are not as homogeneous as the data shown in "the component" level in the SSURGO database and will have some spatial variation. The fuzzy logic system could help reduce the effects on suitability evaluation conducted with the empirical understanding of crop growth constraints and the precise and time-invariant properties in the available data.

A significant gap in our knowledge exists because we do not know the site-specific suitability of marginal land for biofeedstock crops. The overall goal of this study is to evaluate the suitability of marginal land to growth of switchgrass, *Miscanthus*, and hybrid poplar. Specific objectives include: 1) identify marginal land resources in the Upper Mississippi River Basin (UMRB) area; 2) conduct a comparative analysis of marginal land suitability for growth of switchgrass, *Miscanthus* and hybrid poplar based on fuzzy logic modeling; and 3) predict biofuel production from three biofuel crops in the context of land suitability information and the impact on food production in this region.

## 2. Methods

### *2.1 Study area*

The UMRB is located in the center of the Corn Belt in the US, with almost half (43%) of its total area (493,000 $km^2$) covered by row-crop agricultural land (primarily corn and soybean land) (USDA National Agricultural Statistics Service Cropland Data Layer. 2014) and another 16% by pasture land. The great amount of corn production makes this region an important source area not only for food/feed but also for grain based biofuel (Wu *et al.*, 2012) as well as the major contributor of nitrogen losses to the Gulf of Mexico (Srinivasan *et al.*, 2010). The predicted reduction of 20% nitrate nitrogen loss from the Mississippi and Atchafalaya River Basin by producing switchgrass (Costello *et al.*, 2009) indicates the potential of environmentally sustainable production for biofeedstock. Especially, the production of perennial biofuel crops on marginal land has the potential to bring greater environmental benefits. Thus, it is meaningful to evaluate the suitability of marginal land in this region for the production of three promising biofuel crops.

### *2.2 Marginal land in the UMRB region*

This study focused on three marginal land types: 1) cropland and grassland with land capability class (LCC) 3 to 8 (Gelfand et al., 2013) and other agricultural land with LCC 5 to 8; 2) land located within 10 meters along streams and roads (Gopalakrishnan et al., 2009, 2011; Tang et al., 2010), where forest and developed land were excluded from the analysis; and 3) idle/barren/fallow land. After mapping these three types of marginal land, those that were identified as protected lands based on the national Protected Areas Database (PAD-US v1.3) were removed from the analysis. Datasets used to identify these marginal land are described in the Supporting Information (SI) Table S1.

### *2.3 Marginal land suitability evaluation system*

Figure 1 provided a flowchart of methods used in this study. The ultimate products of this study were land suitability class maps for switchgrass, *Miscanthus*, and hybrid poplar. Suitability class was determined based on Land suitability index (LSI), which represented the degree of land suitability for growth of the three targeted biofeedstock crops. The LSI values ranged from 0 to 1, indicating suitability of marginal land for the crops increased from not suitable at all to completely suitable. First, marginal land is identified within the UMRB. Second, factors (limiting factors in the rest of this paper) that might limit the growth of three biofeedstock crops were identified according to literature and expert's opinion and one raster map for each factor were generated. Details of these factors were discussed in the next section (2.3.1). Third, the marginal land area and maps of limiting factors was used as input layers to a suitability evaluation procedure based on fuzzy logic theory (including fuzzification, fuzzy rule inference, and defuzzification). The evaluation system was first applied to locations where switchgrass yield was reported from literature. The LSI values at these sites were compared to observed switchgrass yields for verification of system accuracy. Finally, the system was applied to all marginal land in the UMRB region to generate the suitability maps for three targeted perennial grass. At last, the biomass production was predicted by multiplying marginal land area, yield per hectare, and bioethanol yield per Mg dry biomass. The suitability of marginal land for the three bioenergy crops was used by scaling yield per hectare in the calculation. Details of the calculation were described in section 2.4. Each step is described in detail below. The fuzzy logic system was coded in python (python 2.7) and run in ESRI ArcGIS 10.2.2.

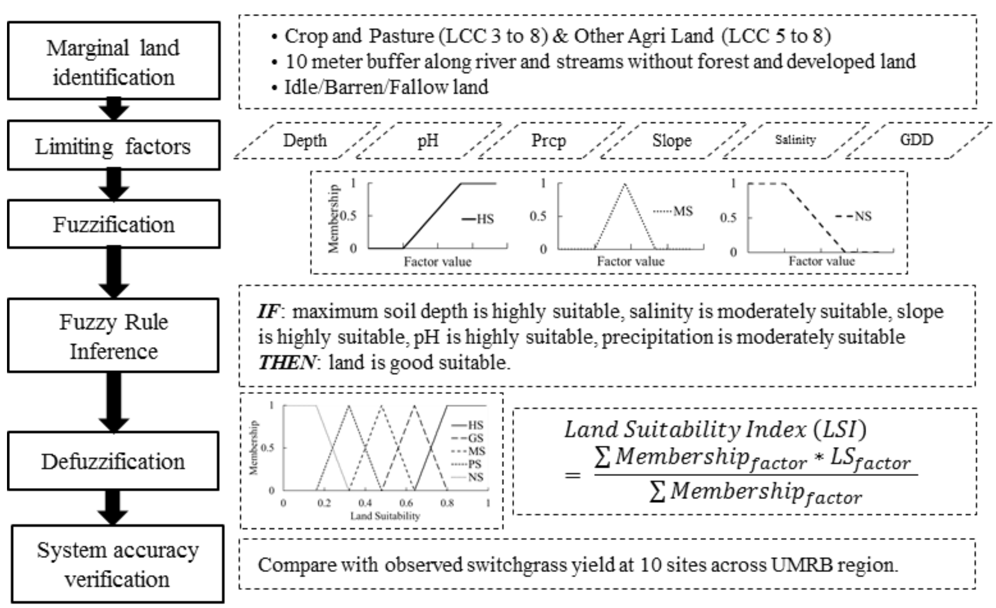


Figure 1 Flowchart of evaluation system based on fuzzy logic theory for marginal land suitability to growth of switchgrass, *Miscanthus* and hybrid poplar.

### *2.3.1 Factors limiting growth of switchgrass, Miscanthus, and hybrid poplar*

Growth of switchgrass, *Miscanthus* and hybrid poplar could potentially be affected or limited by factors either relating to environmental growth conditions like climatic conditions and soil properties, or by management practices such as tillage and fertilization. For characterizing land suitability, only factors relating to the environmental growth conditions were considered. First, a list of environmental factors affecting growth of these biofeedstock crops, and their suitable ranges between which the three biofeedstock crops were suitable to grow (Table 1), was summarized from literature. Then, the identified factors and their suitable ranges were evaluated and finally determined by experts of the three biofeedstock crops. A raster map for each factor was provided in SI Figure S1 and S2 with their corresponding data sources.

Table 1 Factors and their suitable ranges for switchgrass, *Miscanthus* and hybrid poplar

| Factors | Switchgrass | | *Miscanthus* | | Hybrid poplar | | Actual Range in UMRB[3] | |
|---|---|---|---|---|---|---|---|---|
| | Min | Max | Min | Max | Min | Max | Min | Max |
| Maximum soil depth (cm) | 15 | 40 | 15 | 45 | 20 | 40 | 10 | 307 |
| Soil Salinity (dS/m) | 5.0 | 14.5 | 9.8 | 15.0 | 2.2 | 21.4 | 0 | 12 |
| Slope (%) | 15.3 | 4.4 | 15.3 | 4.4 | 15.3 | 4.4 | 0 | 70 |
| pH[1] | 3.7 (7.6) | 6.0 (8.0) | 3.7 (7.5) | 5.5 (8.0) | 3.7 (7.8) | 5.5 (8.0) | 1.0 | 8.0 |
| Growing season precipitation[2] (mm) | 200 | 600 | -- | -- | 240 | 375 | 390 | 664 |
| Growing degree days ($^{o}$C) | 572 | 1200 | 553 | 1600 | 1150 | 1300 | 2367 | 4027 |
| Average annual precipitation (mm) | -- | -- | 500 | 762 | -- | -- | 527 | 1227 |

[1]: For pH, the highly suitable level had a trapezoidal shape membership function. The 4 values were for the four corners of the trapezoid. The order was (for switchgrass as example): 3.7~bottom left, 6.0~upper left, 7.6~upper right, 8.0~bottom right. Shapes of the function was provided in SI Table S2. Detailed description for how these were defined was provided in 2.3.2.

[2]: Growing season ranged from April 1st to September 30th in this analysis.
[3]: Actual Range of variables in the UMRB is the range of each variable based on measured database in the UMRB area. The maps for the actual range of each variable was provided in SI Figure S1 and S2.
--: The values for this factor were not available for the corresponding plants.

***Soil depth***

Soil depth could reduce land suitability for two reasons. First, soil depth might limit root system development if soil was shallower than a certain depth. Second, limited soil depth indicates potentially reduced less and nutrient availability. The suitable ranges of soil depth were determined mainly based on the root system distribution of three biofeedstock crops. Approximately 68% to 78% of total switchgrass roots were reported to occur in the top 0.15 m of soil (Ma *et al.*, 2000; Bolinder *et al.*, 2002) and 94% of coarse roots located in the upper 0.4 m of soil (Garten & Wullschleger, 1999). For *Miscanthus*, an increase in root distribution was observed up to 0.45 m even though 90% of their roots concentrated on the upper 0.35 m soil (Neukirchen *et al.*, 1999; Monti & Zatta, 2009). The recommended minimum planting depth was 0.1 m and a minimum value of 0.15 m was determined for *Miscanthus* for the minimum need of root development (Williams & Douglas, 2011). In the case of hybrid poplar, 0.2 m was selected as minimum value because only 17 to 25% of coarse and 11 to 24% of fine root biomass distributed in this depth of soil (Fortier *et al.*, 2013). This was considered inadequate for hybrid poplar growth. While 61 to 73% of coarse and 60 to 78% of fine root biomass distributed within 0.4 m soil and this depth was selected as the maximum value.

***Soil salinity***

High soil salinity could affect plant growth and limit crop yields by causing low osmotic potential of soil solution and affecting nutritional imbalance (Ashraf & Harris, 2004). Switchgrass is reported to have a low emergence and poor stand establishment at 5 dS/m soil salinity (Kim *et al.*, 2012) and could not survive in soils with salinity exceeding 14.5 dS/m (Dkhili & Anderson, 1990). Similarly *Miscanthus* growth was restricted when salinity was 9.8 dS/m and plant did not survive under 15 dS/m soil salinity (Ye *et al.*, 2005; Agnieszka Płażek, 2014). Growth of hybrid poplar can be limited by soil salinity levels of 4.5 dS/m and greatly reduced by soil salinity greater than 21.4 dS/m (Steppuhn *et al.*, 2008).

***Slope***

High slope could reduce land suitability by reducing machine operation safety and increasing the risk of soil erosion. Slope values used in existing land suitability evaluation for traditional crops and perennial crops under non-irrigated condition were summarized from literature (SI Table S2). Included studies generally used the 5 suitability classes suggested by the Food Agriculture Organization of the United Nations (FAO) (Hanson & Johnson, 2005). The average values for the thresholds of the highest suitability class (4.4%) and not suitable class (15.3%) were selected as the minimum and maximum values for slope variables used for the three biofuel crops.

***pH***

Proper pH ranges are important for plant growth. The optimal pH range for switchgrass growth was from 6 to 8 (Hanson & Johnson, 2005) and seedlings of switchgrass could tolerate pH from 3.7 to 7.6 (McLaughlin & Adams Kszos, 2005; Parrish & Fike, 2005). For *Miscanthus*, the optimal pH range for its growth was 5.5 to 7.5 and a pH of 8 was reported to limit *Miscanthus* growth (Williams & Douglas, 2011). Hybrid poplar was recommended to grow on soils with pH ranging from 5.5 to 7.8, and a pH greater than 8.0 was considered to limit poplar growth (Segal R, 2015). The minimum value of pH for *Miscanthus* and hybrid poplar was not available. Thus, a pH of 3.7 available for switchgrass was used for the other two crops as an assumption.

***Climatic conditions***

Precipitation and temperature are the two major variables that could greatly impact growth and final yield of biofuel crops (Matt A. Sanderson, 1997; Joss *et al.*, 2008; Maughan *et al.*, 2012). Possible precipitation and temperature variables include as average, maximum, and minimum annual and growing season precipitation and temperature. Upland switchgrass yield is limited by growing season (April 1st to September 30th) precipitation and yield, with low biomass production when the growing season precipitation was less than 200 mm. Biomass yield was not limited when growing season precipitation exceeded 600 mm (Davis *et al.*, 2008). Growing degree days (GDD) represented the cumulative heat requirements for plant growth. Upland switchgrass required a minimum GDD of 578 with a base temperature at 10 $^{o}$C to complete leaf and stem elongation

(Sanderson & Wolf, 1995) and 1200 GDD to reach maturity (Trybula *et al.*, 2014). For *Miscanthus*, 500 mm average annual precipitation (growing season precipitation threshold for *Miscanthus* growth was not available) was considered the minimum amount for its growth, whereas 762 mm (30 inches) was considered ideal precipitation (Jensen *et al.*, 2013). *Miscanthus* required a minimum GDD of 553 for floral initiation (Porzio *et al.*, 2012) and 1600 GDD to reach maturity (Trybula *et al.*, 2014). The suitable ranges of growing season precipitation and GDD values for hybrid poplar were retrieved from Joss *et al.* (2008). By comparing suitable ranges of GDD with the actual GDD ranges in the UMRB, GDD was not a limiting factor and was not used in the following land suitability evaluation procedures.

### *2.3.2 Fuzzification*

Fuzzification is the process in which the values of environmental factors were converted to membership values using fuzzy membership functions. The purpose of this method was to map the crispy factor values into common scale for further analysis. The methods used by Joss *et al.* (2008) was used in this paper. For each environmental factors, 3 suitability levels were created: highly suitable (HS), moderately suitable (MS) and not suitable (NS). One membership function was defined for each suitability level. The function and shapes of all environmental factors are provided in SI Table S3.

The membership function for HS level was developed first using the minimum and maximum values summarized in Table 1. For maximum soil depth, and growing season precipitation, the increase of values for these two factors increased the potentially suitability of the land for growth of plants. Thus, the membership functions for HS level of the two factors were increasing functions. The membership value started to increase from 0 at the minimum factor value (for example, 15 cm of maximum soil depth for switchgrass) to 1 at the maximum factor value (for example ≥40 cm of maximum soil depth for switchgrass). This indicated that a land did not belong to the group of HS level when values of these two factor was smaller than their minimum value, and completely belonged to that level when larger than their maximum value. For slope and salinity, the membership functions for the HS level were decreasing functions because the larger the values of these two factors, the less one land was suitable for the crop growth. For these two factors, the membership values started to decrease from 1 at the factor's minimum value (for example, 6 of slope for switchgrass) to 0 at the factor's maximum value (for example, 18 of slope for switchgrass). This indicated that a land completely belonged to the group of HS level when values of these two factor were smaller than their minimum values and not belong to the group of HS level when larger than their maximum values. For pH, the membership function for the HS level had a shape of trapezoid. The reason was because both the increase of pH to 14 from around 7 and decrease of pH values to 1 reduced the suitability of land for crop growth. Thus, the membership values started to decrease from 0 at the minimum value (bottom left in Table 1) to 1 at the maximum value (upper left in Table 1) when the value was less than 7. The membership value started to decrease from 1 at the maximum value (upper right) to 0 at the minimum value (bottom right).

Based on the membership functions for the HS levels, the membership function for NS levels were the inverse of those for HS levels. The membership functions for MS had a triangle shape. Membership values of a land for the MS level decreased from 1 at the average of maximum and minimum factor value (for example, 27.5 cm of maximum soil depth for switchgrass) to 0 at the maximum or minimum factor values. This indicated that a land completely belonged to the group of MS level at the average value and did not belong to the group when the values were smaller than the minimum or larger than the maximum factor value.

### *2.3.3 Fuzzy rule inference*

This step intended to determine the membership value of one piece of land area to 5 integrated suitability levels based on all environmental factors instead of just one factor. The 5 suitability levels include: integrated highly suitable (iHS), integrated good suitable (iGS), integrated moderately suitable (iMS), integrated poorly suitable (iPS) and integrated not suitable (iNS). The membership values indicated the degree of a land's belongingness to each of the 5 integrated suitability levels. The determination of membership value based on all environmental factors was completed by using empirical IF-THEN rules. One example of the IF-THEN rule was "IF the maximum soil depth is HS, salinity is MS, slope is HS, pH is HS, precipitation is MS, and GDD is HS, THEN, the land is iGS". The suitability levels used in the IF part was the 3 suitability levels from the fuzzification step, and those used in the THEN part was 5 integrated suitability levels. The following rules were used in generating a single IF-THEN rules:

- When there is at least one not suitable, the combinations will be considered as integrated not suitable (iNS).
- When there are all highly suitable variables, the combination will be considered as integrated highly suitable (iHS)
- When there is one marginally suitable variables, the combination will be considered as integrated good suitability (iGS)
- When there are 2 and 3 marginally suitable variables, the combination will be considered as integrated marginal suitability (iMS).
- When there are 4 marginally suitable, the combination will be considered as integrated poor suitable (iPS)

The minimum membership value of all components in the IF part was assigned as the membership value for integrated suitability level of the land in the THEN part. For each suitability level, one or several rules might be included from different combination of IF part. The maximum value from different rules with same integrated suitability level in the THEN part was assigned as final membership values of the land for that suitability level. This IF-THEN rule was essentially calculating the logical intersections and unions of fuzzy sets for suitability levels defined in the fuzzification step. By using a combination of calculating first intersections and then unions, the fuzzy rule inference system achieved a balance between the two extremes achieved by using only one logic interactions (intersection or union) (Joss *et al.*, 2008).

### *2.3.4 Defuzzification*

Defuzzification converted the membership values of land for each of 5 integrated suitability levels from fuzzy rule inference step into one representative value, which was called the Land Suitability Index (LSI) in this study. LSI represented the overall suitability of each land pixel for growth of targeted biofeedstock crops. LSI was calculated using the Center of Maximum (COM) defuzzification method. First, membership functions were developed (SI Figure S3) to represent the membership values of LSI for each suitability level. Mean of the minimum and maximum LSI values for each suitability level was then determined. At last, a final weighted average LSI was achieved by using the membership values determined for each suitability level in the fuzzy rule inference as weights (Figure 1).

### *2.3.5 Sensitivity of LSI values to threshold changes*

In order to determine the validity of the model and the selected factor and parameters in the fuzzy logic model (upper and lower bounds as thresholds in the model), a sensitivity analysis was conducted using the One-factor-At-a-Time (OAT) method (van Griensven et al., 2006). Details of the steps and procedure of the sensitivity was provided in the second part of the supporting information.

### *2.3.6 LSI accuracy verification*

In existing literatures, accuracy of land suitability from fuzzy logic based procedure (Bolinder *et al.*, 2002; McLaughlin & Adams Kszos, 2005) were checked with experts' opinion or empirical opinions. The accuracy of LSI values calculated in this study were checked by comparing the measured yield values of switchgrass and *Miscanthus* against LSI values. This method was considered more practical and reliable. LSI was a concept that could not be measured objectively. However, yield of crops could be considered as an objective indicator that could reflect the degree of land suitability. Switchgrass and *Miscanthus* were tested in multiple sites across a wide geographic range across the US in the last two decades. Yield data from different sites with their geographic location (Latitude, Longitude) were summarized from literature (SI Table S4). Totally, data from 9 sites were included for switchgrass and 10 sites for *Miscanthus* in the validation. Land in these location included both marginal and non-marginal land. It was reported that the switchgrass yield from both marginal and non-marginal land did not show significant difference (Wullschleger *et al.*, 2010). The relationship between the yields and LSI values at all sites were analyzed using the regression module in SAS9.4.

After the verification, LSI values for switchgrass, Miscanthus, and hybrid poplar were generated using the same data sources, parameters and procedures as used in the verification step. The LSI maps was reclassified into 5 suitable classes, similar as used by Reshmidevi et al (2009). The classes included: not suitable (0 ~ 0.3), poorly suitable (0.3 ~ 0.45), moderately suitable (0.45 to 0.6), good suitable (0.6 ~ 0.8), highly suitable (0.8 ~ 1).

### *2.4 Biofuel and food production prediction*

In order to understand the potential of marginal land for biofuel production and impacts on food production in the UMRB region, biofuel prediction was calculated for both three bioenergy crops and two traditional crops (corn and soybean) grown on marginal land. For the three crops, biofuel production was calculated in two ways to explore the impacts by incorporating marginal land suitability on the prediction of potential contribution from marginal land to biofuel production in the UMRB. The first way used an average yield of switchgrass, *Miscanthus* and hybrid poplar from field experiments for all marginal lands. The yield values used are provided in SI Table S4-5. The average yield used for switchgrass was 9 Mg/ha, for *Miscanthus* 24 Mg/ha, and for hybrid poplar 8 Mg/ha. In the second method, yield of biofeedstock crop was scaled down by the LSI values. This method assumed that the average yield could be achieved on marginal land when its LSI value was 1. For example, if LSI values for one land was 0.6, the yield of switchgrass would be 5.4 Mg/ha, of *Miscanthus* would be 14.4 Mg/ha and of hybrid would be 4.8 Mg/ha. A bioethanol yield of 80 gal/dry Mg biomass, which was close to the average published bioethanol yield that could be achieved practically from lignocellulose biofeedstock (Lovett *et al.*, 2009; Gao *et al.*, 2014; Liu *et al.*, 2015), was used for all three biofuel crops to calculate the total bioethanol that could be produced from marginal land in the UMRB region. For corn and soybean, the yield was simulated using the Soil and Water Assessment Tool (SWAT) model. In the model, marginal land was represented in detail for the UMRB region and details of the model was available in Feng et al., (2016).

## 3. Results

### *3.1 Marginal land availability*

Table 2 presents the availability of marginal land in the UMRB area. Marginal land with LCC 3 to 4 and 5 to 8 are separated because LCC 1 to 4 are suitable for cultivation of traditional crops and land with LCC 5 to 8 are not suitable. In this study, the targeted crops are all perennial plants and might be suitable for growing on land with LCC ranging from 5 to 8. As shown in Table 2, all types of marginal lands comprise 23% of the entire UMRB area. The largest areas of marginal land come from cropland with LCC 3 to 4, followed by grassland with LCC 3 to 4 and grassland with LCC 5 to 8. Land area under cropland with LCC 5 to 8 is relatively small, as well as other crops with LCC 5 to 8. Combined areas of marginal lands from buffer area and idle/barren/fallow lands are much smaller than those from Type 1 marginal land. Overall, 29% of cropland in the UMRB area are marginal land and nearly two thirds (62.3%) of grasslands are identified as marginal land.

Table 2 Marginal land availability in Upper Mississippi River Basin (UMRB)

| Types of marginal land | | Area (km$^2$) | % over total marginal land area | % over total UMRB area | % over corresponding original land class area |
|---|---|---|---|---|---|
| Type 1 | Cropland with lcc 3 to 4 | 56,426 | 51 | 11 | 27 |
| | Cropland with lcc 5 to 8 | 3,965 | 4 | 1 | 2 |
| | Grassland with lcc 3 to 4 | 36,423 | 33 | 7 | 47 |
| | Grassland with lcc 5 to 8 | 11,139 | 10 | 2 | 14 |
| | Other crops with lcc 5 to 8 | 172 | 0.15 | 0.03 | 5 |
| Type 2 | 10 m strips along stream | 2,894 | 3 | 1 | |
| | 10 m strips along road | 41 | 0.04 | 0.01 | |
| Type 3 | Idle/fallow/Barren | 625 | 1 | 0.13 | |
| Summary | Total area of marginal land in UMRB | 111,660 | 100 | 23 | |
| | Total area of UMRB | 492,027 | | 100 | |

### *3.2 LSI accuracy validation*

Figure 2 presents the results for validation of LSI values calculated with the fuzzy logic based land suitability framework against observed yield for switchgrass and *Miscanthus*. The trend for the changes in switchgrass *Miscanthus* yield and changes in LSI values indicated that the calculated LSI value effectively ($p<0.05$) explained the yield of switchgrass and *Miscanthus* from these lands. The yield value, corresponding LSI value and reference for each site is provided in SI Table S4.

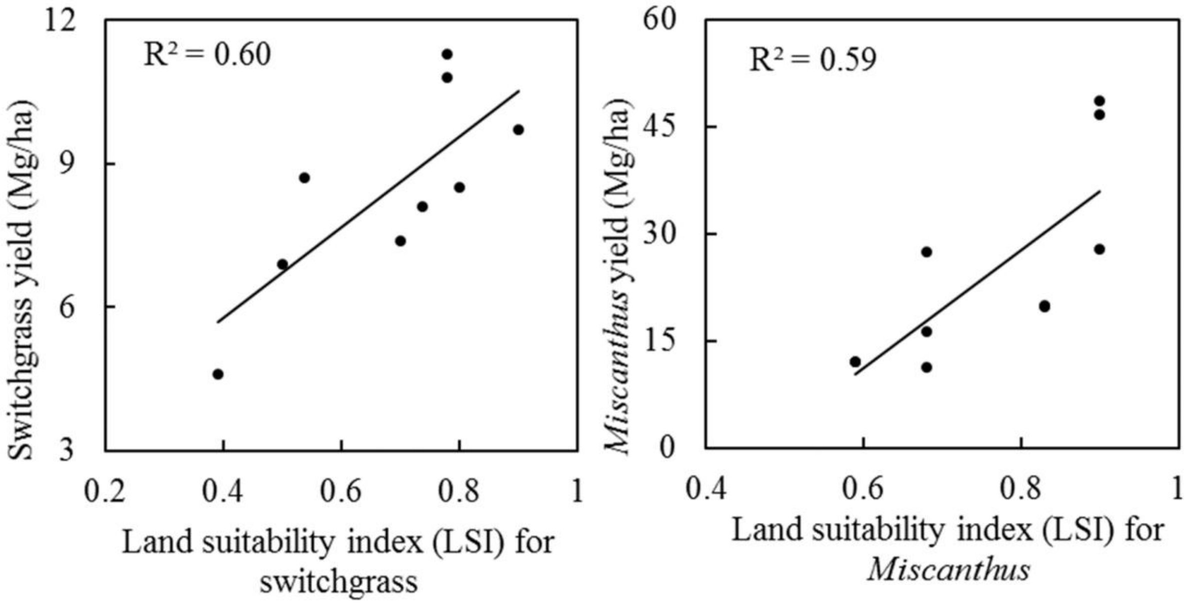


Figure 2 Trends of Land suitability index (LSI) for sites where switchgrass and *Miscanthus* yields were available from previously published studies (SI Table S4).

### *3.3 Marginal land suitability*

Figure 3 and Figure 4 presented the area and spatial distribution of 5 suitability classes based on LSI of switchgrass, *Miscanthus*, and hybrid poplar. The total area of land with classes of not suitable, poor suitable, and moderate suitable were 38% for switchgrass, 41% for *Miscanthus*, and 34% for hybrid poplar. Area of land with class of not suitable were similar for both three crops. For land with classes of poorly and moderately suitable, the area was largest for *Miscanthus*, followed by switchgrass and then hybrid poplar. The area of land with good suitable class was much higher for switchgrass than for *Miscanthus* and hybrid poplar, while the reverse pattern happened for land with highly suitable classes.

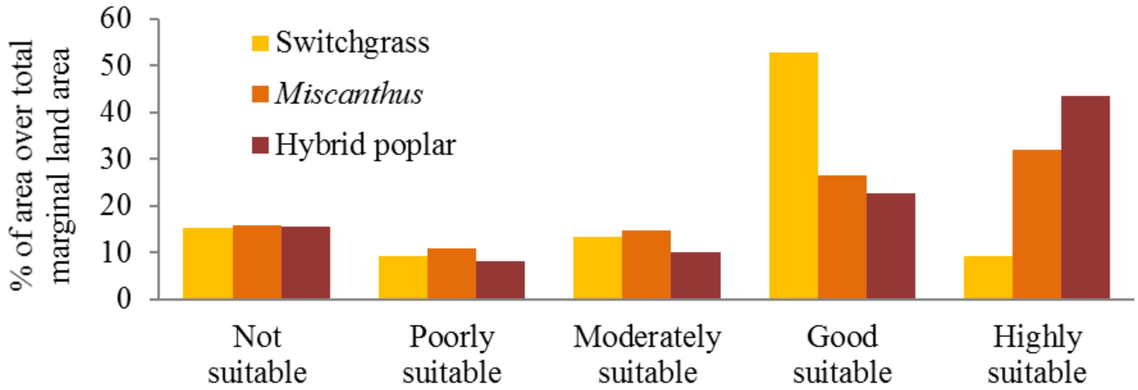


Figure 3 Histogram of areas for each suitability class

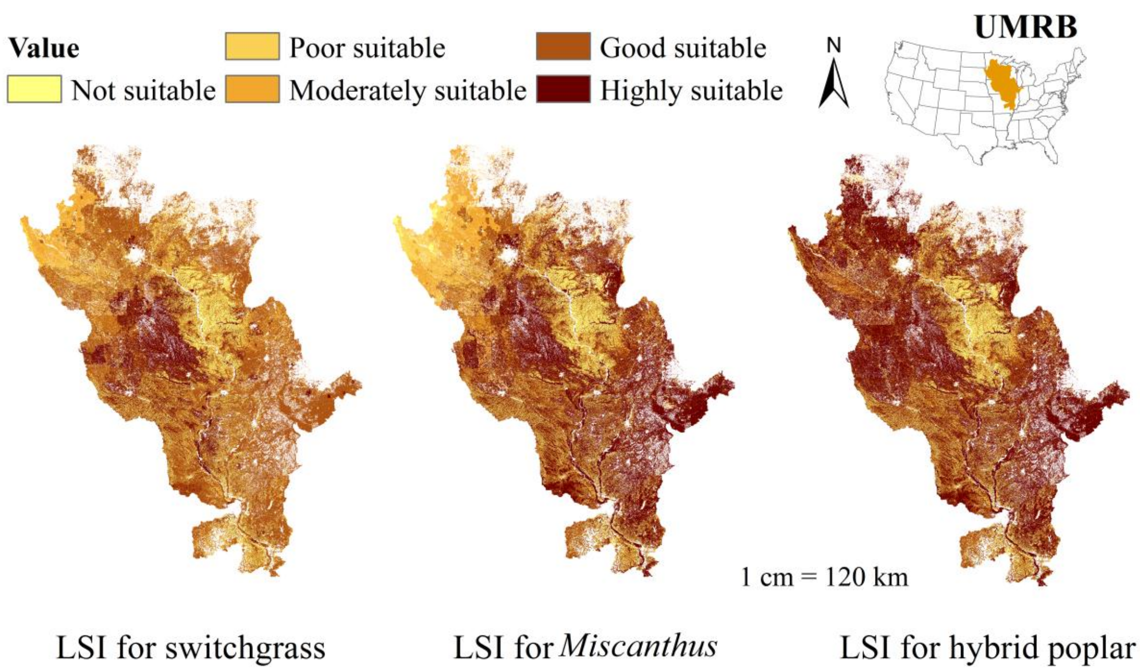


Figure 4 Land Suitability maps (LSI) for switchgrass, *Miscanthus*, and hybrid poplar in the Upper Mississippi River Basin (UMRB).

### *3.4 Biofuel production in UMRB*

Due to the higher average measured yield of *Miscanthus*, the total biomass and predicted bioethanol from this perennial biofeedstock crop on marginal land in the UMRB region is about 3 times that from switchgrass or hybrid poplar (Table 3). When land suitability information was incorporated into biomass production prediction, the predicted biomass and bioethanol from these three crops were about two thirds of the prediction made with average yield of these biofuel crops. The final prediction of bioethanol production was close to that of switchgrass. By converting marginal land from cropland with LCC 3 to 8, food production in this region will be reduced. Simulated total biomass production from cropland with LCC 3 to 8 were 24% and 36% of biomass production for corn (144 million Mg) and soybean (24 million Mg) in the whole UMRB region. The bioethanol from biomass of corn on marginal land were about 1/5 to 1/2 of bioethanol produced from bioenergy crops considering land suitability information and from biomass of soybean were about 1/10 to 1/25.

Table 3 Biomass and biofuel yield prediction with average biomass yield and marginal land yield based on LSI for switchgrass, *Miscanthus*, and hybrid poplar from marginal land, and with simulated corn and soybean by the SWAT model in the UMRB region. Biofuel was calculated with a bioethanol yield of 80 gal/dry Mg biomass for bioenergy crops, 90 gal bioethanol/dry Mg corn starch, and 56 gal biodiesel/dry Mg soybean.

| | With average yield | | With marginal land yield based on LSI | |
|---|---|---|---|---|
| | Biomass (Million Mg) | Biofuel (Billion Liter) | Biomass (Million Mg) | Biofuel (Billion Liter) |
| Switchgrass | 101 | 30 | 59 | 19 |
| *Miscanthus* | 268 | 79 | 159 | 49 |
| Hybrid Poplar | 89 | 26 | 58 | 19 |
| Corn | 34 | 11 | | |
| Soybean | 9 | 2 | | |

## 4. Discussion

### *4.1 Marginal land identification*

In literature, marginal land are defined based on 5 aspects. These aspects include economic, biophysical, location, current condition or environmental aspects (Peterson & Galbraith, 1932; Gopalakrishnan *et al.*, 2009; Cai *et al.*, 2011; Kang *et al.*, 2013a). In this study, the types of marginal land defined in terms of their biophysical, location and current location aspects are considered. Marginal land defined by LCC includes crop and pasture land with marginal LCC. This is defined because the Renewable Fuel Standard 2007 specifies that land for biomass production could only come from current crop and pasture land (Schnepf & Yacobucci, 2010). In addition, LCC is an established database that indicates the suitability of land for cultivating current annual agricultural crops. The inclusion of marginal idle/barren/fallow land is triggered by the potential environmental benefits by growing perennial grasses on buffers along streams and roads (Gopalakrishnan *et al.*, 2009). As for type 3 marginal land, they are currently not engaged in agricultural production and could avoid impacting current agricultural production. These three marginal land types meet the expectation of candidate land resources for biofuel development. The total area of marginal land identified is close to the land area identified in Gelfand *et al* (2013) using similar criteria. The framework developed in this study could serve as a starting point for comprehensive suitability evaluation of other marginal land types. Similarly, additional factors that affect the growth of biofuel crops may also need to be evaluated. For example, individual brownfields may have unique characteristics that are detrimental for growth of specific biofuel crops, but not others.

For the marginal land types included in this study, a competition of land between food/feed and fuel production may not be completely avoided. With the exception of marginal idle/barren/fellow land, marginal land defined by LCC and from buffer area all contain land currently used for crop production. They are major sources of marginal land. If they were converted to biofeedstock crop production, agricultural production will be reduced in UMRB area. From the productivity point of view, these lands are suffering certain degrees of limitation for agricultural production. Their poor performance of traditional crops might be a good reason for conversion to biofeedstock crops, which generally have lower input requirements than traditional crops.

### *4.2 Suitability evaluation*

This study used a well-established land suitability evaluation procedure based on fuzzy logic theories. This method has been developed and applied in a large number of studies (Malczewski, 2004; Sicat *et al.*, 2005; Reshmidevi *et al.*, 2009; Elsheikh *et al.*, 2013) and even for biofeedstock crops (Joss *et al.*, 2008; Lewis *et al.*, 2014). Even though this study focused only on marginal land area, the framework including the limiting factor values will also be applicable on other land types (such as prime farm land) to evaluate their suitability for growth of these three biofeedstock crops. The LCC class for identifying marginal land provide some insights into the suitability for crop growth, but the targets of LCC classes are for traditional annual crops. LCC classes do not indicate the suitability of land for perennial biofeedstock crops. The evaluation procedure in this study provide more cogent information on land suitability for growth of switchgrass, *Miscanthus*, and hybrid poplar.

The results of validating LSI value from this procedure provide evidence for the effectiveness of the suitability map for indicating the potential growth of targeted biofeedstock crops. Nonetheless, several sources of uncertainties should be noted. The first source of uncertainty comes from determining the variables and their suitable ranges. The results from the sensitivity analysis of the LSI values calculated with the fuzzy logic model indicated that the limiting factors selected in this paper for determining land suitability were scientifically valid. The simulated LSI values were sensitive to the proper parameters and the thresholds were meaningful in reality. For example, the LSI values were most sensitive to maximum values of salinity (the upper bound). In reality, higher reality resulted into poorer suitability. Even though the variables included in our analysis cover most of the variables considered in the past analysis of suitability for the biofuel crops (Joss *et al.*, 2008; Lovett *et al.*, 2009), there are other variables that are not included in this analysis, such as dryness index (Lewis *et al.*, 2014). It is considered that the effect of water is reflected partially by the precipitation factor. These factors are determined based on empirical knowledge and expert's opinions. It has been pointed out that this way of selecting variables and their impacts is subjective (Elsheikh *et al.*, 2013). In addition, variables and their suitable ranges may vary with cultivation. For example, differences exist between upland and lowland ecotypes of switchgrass for important agronomic traits, like yield, winter hardiness, etc. This is also true for hybrid poplar, which also has many different genotypes. These differences in relationships between cultivars and environmental variables can also introduce uncertainties in the shapes of membership functions. A piece-wise linear function is selected due to its simplicity and its capability of representing the general roles played by each variable on crop growth. Besides the uncertainties from the distance between this linear function and the true relationships between environmental variable and crop growth, the different responses from cultivars of the same crop will result into differences of model output sensitivity to shapes of membership functions. However, a lack of training data to determine the relation between land property and suitability for crop growth is the main reason for not developing more predicting membership functions between variables and suitability of land for growth of targeted crops.

The last source of uncertainty comes from the data used in assessment of the suitability map accuracy. As shown in SI Table S4, the average yield from experimental fields for switchgrass contains different degrees of variance, ranging from less than 1Mg/ha to more than 3 Mg/ha. These variations could be caused by an array of factors including differences in environmental conditions, management practices, and cultivars. In this study, only environmental conditions are used. Even though the relationship between yield and the LSI achieved based on environmental conditions are significant, it is not clear how much contributions to the yield difference are made by other factors. In addition, some management practices might have changed the land properties, thus the input values used in this study. For example, pH values could be managed by liming application. While, the COM defuzzification method could account for impacts from this point because small changes of input values will not change the best compromise value for LSI value. The LSI values were not validated for *Miscanthus* and hybrid poplar due to limited biomass production data. These major sources of uncertainties should be considered and processed in future research to increase the confidence of the marginal land suitability for biofeedstock crop production.

### *4.3 Biofuel production*

The bioethanol yield predicted with average yield in this study are comparable to those predicted in other studies. For example, Srinivasan *et al.* (2010) predicted that 42% of all agricultural land in UMRB region planted with switchgrass could produce 345 Million Mg biomass with the simulation by the Soil and Water Assessment Tool (SWAT) model. In this study, the total area of marginal land is 23% of the UMRB region area, which covers 29% (close to one thirds) of corn/soybean land. The biomass production is calculated using yield from experimental sites, instead of farmers' land which generally produce smaller yield than experimental sites. The estimation with yield from farmer's land is not feasible currently because large area production of these perennial crops are not available. While, the current breeding efforts made on these perennial crops could help improve the yield of these crops to the average yields used here. The estimation of biomass and biofuel production here are considered efficient with current knowledge on yield performance of these biofeedstock crops. The predicted of biomass production was 101 Million Mg, about one thirds of the total biomass expected by Srinivasan *et al*. (2010). When marginal land suitability was considered, the biomass and bioethanol prediction was reduced by one-third for all three biofuel crops, but they could still make substantial contribution to the biofuel development goals in the Energy Independence and Security Act of 2007, which mandated that 79 billion liters cellulose biofuel be produced annually by 2022.

By converting marginal lands to producing biofuel crops, food production in the UMRB region is impacted. It is estimated that 24% of total corn and 36% of total soybean production from all agricultural land in this region will be lost due to the land use conversion. However, the biofuel production by from harvested bioenergy crops are much more than harvested corn and soybean on marginal land. This indicates that growing bioenergy crops on marginal land can potentially reduce the competition of land for food in this region by using less food produced from non-marginal lands for bioenergy conversion.

## 5. Conclusion

In summary, this study presents the application of a well-established land suitability evaluation framework based on the fuzzy logic theory. The results of this study characterizes great spatial variance of land suitability for three promising biofeedstock crops, switchgrass, *Miscanthus* and hybrid poplar. Specifically, 23% of the UMRB area are identified as marginal land, and 60% of the marginal land area are moderately to highly suitable for growth of switchgrass, *Miscanthus* and hybrid poplar. The major factor that limited the growth for these biofuel crops were steep slopes, high salinity, or lower soil pH. When suitability of marginal land is considered, the predicted bioethanol production is two thirds of predictions made by considering that the land was all suitable for biofuel crop growth. The information underscores the importance of marginal land's potential contribution for biofuel development and for reducing land competition between food and fuel production. It also underscores the importance of considering marginal land suitability, which is critical for proper biofeedstock placement on the landscape and accurate assessment of biofuel production potential in the UMRB. If less suitable marginal land were going to be used for biofuel crop production, management practices to improve their suitability may need to be developed and implemented.

## 6. Acknowledgement

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). We also would like to acknowledge GIS data and support provided by Larry Theller, Department of Agricultural and Biological Engineering, Purdue University, and the help provided by Dr. James Kiniry (Research Agronomist from Agricultural Research Service, United States Department of Agriculture).

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