



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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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 and 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 and 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 and Büyüktaktin, 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 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

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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 and 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 and 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 and 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 km²) 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 m 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

Fig. 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

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