Computers and Electronics in Agriculture 103 (2014) 39–47

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

A fuzzy logic-based spatial suitability model for drought-tolerant switchgrass in the United States

Sarah M. Lewis [a], Gary Fitts [b], Maggi Kelly [a,*], Larry Dale [b]

[a] University of California, Berkeley, 130 Mulford Hall #3114, Berkeley, CA 94720-3114, USA
[b] Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Received 30 April 2013
Received in revised form 15 January 2014
Accepted 12 February 2014

Keywords:
Switchgrass
GIS
Fuzzy modeling
Bioenergy
Drought

ABSTRACT

Switchgrass (*Panicum virgatum*) has been targeted by the U.S. Department of Agriculture as an exemplary bioenergy crop, however it requires a significant amount of water and experiences reduced yields in water-stressed conditions. To avoid competition for prime agricultural areas, lands that receive adequate rainfall but are marginal due to highly variable timing of rain are potentially ideal locations to grow drought-tolerant biofuels. As scientists develop a modified variety of switchgrass that can withstand periods of drought while not substantially affecting overall yield, it is important to identify the potential geographical niche for this xerophytic crop to maximize its environmental and economic sustainability. This project uses a spatial suitability modeling approach that incorporates fuzzy logic and utilizes both physical and economic variables. We assess several fuzzy overlay techniques to identify and synthesize tradeoffs between suitability criteria. Our results highlight the Great Plains region of the United States as a suitable region, and within this area we focus on Kansas for a more detailed analysis to calculate land areas within varying dryness index thresholds. For this we develop a specialized dryness index using high resolution (spatial & temporal) weather and soil data to provide a spatially explicit measure of dry spell severity for switchgrass across a landscape. We estimate that 80% of the suitable land area in Kansas falls within a dryness index equivalent to about four 22-day long dry stretches, or one 45-day long dry stretch. By identifying the dryness threshold where land area is maximized, the results of this analysis inform the development of drought-tolerant varieties of switchgrass and identify marginal areas where efforts to plant such a species may prosper.

1. Introduction

As world-wide energy demand increases, there is growing pressure for renewable energy sources to help meet requirements and at the same time mitigate for climate change. While no single type of renewable energy will fulfill all of our energy needs, biofuels promise to become a growing sector of the global renewable energy market. In the 1980s the U.S. Department of Agriculture (USDA) recognized switchgrass (*Panicum virgatum*) as an exemplary mass bioenergy crop. The potential recognized benefits of switchgrass include both its ability to grow on non-prime agricultural land as well as its potential to enhance energy sustainability by producing more renewable energy than nonrenewable energy consumed when converted to cellulosic ethanol (Schmer et al., 2008). Since then many studies have illustrated the potential benefit of non-food, second generation biofuel crops, also known as advanced biofuels (Gelfand et al., 2013; Tilman et al., 2006; Youngs and Somerville, 2012). As a result, a growing number of countries are incorporating mandates for second generation biofuels into policy. In 2007 the United States Congress passed the Energy Independence and Security Act (EISA) which creates a more aggressive Renewable Fuel Standard (RFS2), including a call to increase domestic production of 16 billion gallons of cellulosic biofuels per year by 2022 (Sissine, 2007). Out of a growing concern that such a large mandated sum of biofuels will compete for prime agricultural land, there is increasing pressure to plant biofuels on marginal, abandoned, or otherwise non-agricultural land (Searchinger et al., 2008). However, it is not straightforward how to locate such lands.

Spatial suitability modeling with Geographical Information Systems (GIS) is increasingly used as a technique to identify potential locations for renewable energy generation (Angelis-Dimakis et al., 2011; Ramachandra and Shruthi, 2007; Voivontas et al., 1998), including the placement of geothermal (Noorollahi et al.,

* Corresponding author. Tel.: +1 510 642 7272.
E-mail addresses: maggi@berkeley.edu (M. Kelly), LLDale@lbl.gov (L. Dale).

http://dx.doi.org/10.1016/j.compag.2014.02.006
0168-1699/

2008; Yousefi et al., 2007), wind (Hansen, 2005; Rodman and Meentemeyer, 2006), solar (Janke, 2010) and bioenergy (Lovett et al., 2009; Odeh et al., 2011). The most common spatial models used in GIS-based suitability studies fall into two fundamental classes of multicriteria evaluation (MCE): Boolean overlay or Weighted Linear Combination (WLC) (Malczewski, 2004). In Boolean and WLC models, a common type of operation employs a distinct threshold of suitability. In Boolean overlay models, each criterion is classified into two subsets delineating whether or not a particular area is suitable. Criterion maps are then layered using logical connectives (i.e. AND, OR). One primary shortcoming of Boolean analysis is that criteria can only be TRUE or FALSE, which creates discrete boundaries between variables. This imposes artificial precision on mapped results and fails to model more nuanced degrees of suitability. In contrast, models that use WLC bin each criterion into categories. These categories are then weighted based on their importance as decided by professionals in the field, so when combined, one criterion with relative low suitability can be recompensed by the high score of another. Because binning still requires discrete thresholds, such models are also inherently rigid and do not best represent the real world (Jiang and Eastman, 2000).

Numerous studies identifying marginal lands for specific biofuel crops have used Boolean approaches using linear combination GIS overlays (Campbell et al., 2008; Gopalakrishnan et al., 2011; Zhuang et al., 2011). One Australian analysis by Odeh et al. (2011) identified marginal lands for two biofuel crops based on an overlay of climatic and physical variables. Similarly, in the United Kingdom, Lovett et al. (2009) identified marginal lands for Miscanthus with a GIS overlay of 11 physical and socio-economic factors along with sub-prime agricultural land classification classes. Although less common, at least one study mapping marginal land incorporated WLC into their model to quantify marginal land for agro-fuel crops in Italy by applying weights to the input criteria depending on level of importance as defined by the user (Tenerelli and Carver, 2012).

This paper adopts a different approach and employs a spatial suitability model based in fuzzy set theory (Zadeh, 1965). As compared to traditional overlay models, fuzzy logic better addresses data variability, imprecision, and ambiguity (Hall et al., 1992). Unlike Boolean logic or WLC, fuzzy logic assigns a continuous membership value between 1 and 0 for each criterion. Typically, fuzzy logic values approaching 1 are considered more suitable and values approaching 0 are considered less suitable. In a fuzzy set, the concept of suitability, or 'membership,' is not definitive because all objects belong to the set in varying degrees. This approach better represents the continuous nature of biophysical and economic variables (Malczewski, 2004). The fuzzy spatial suitability model provides a formal framework to represent the uncertainty of where a threshold of suitability falls within a continuous landscape. In this way, fuzzy logic incorporates variation in expert judgment and provides more flexible classifications of suitability (Jiang and Eastman, 2000).

Recent spatial suitability studies that incorporate fuzzy set theory and GIS-based suitability modeling frameworks to identify ideal sites for renewable energy generation include Charabi and Gastli (2011)), who assessed land suitability for large Photovoltaic farms in the country of Oman with GIS-based spatial multi-criteria evaluation approach using Fuzzy Logic Ordered Weighted Averaging (FLOWA). Cai et al. (2011) conducted a global study targeted towards mapping marginal land for generic cellulosic biofuel species using MCE and fuzzy logic modeling. They first identified land with marginal productivity based on soil productivity, slope, soil temperature regime, and humidity index. Datasets were transformed into standardized layers using fuzzy membership functions based on triangular membership functions (Pedrycz, 1994), and were then disaggregated to produce a final productivity index over which the team layered results with land cover to create four scenarios of land availability restriction. To the author's knowledge, the paper presented here is the first to use a fuzzy overlay approach specifically for mapping suitable areas for a specific biofuel species-switchgrass (*P. virgatum*).

In addition to locating enough land to meet bioenergy mandates, an added concern is that the frequency of extreme weather and drought has increased over the last century (Dai et al., 2004; Regonda et al., 2005; Wang et al., 2010) and is expected to intensify with climate change (Karl and Trenberth, 2003; Mishra et al., 2010; Wehner et al., 2011). These changes make it increasingly important to grow drought-tolerant biofuels on dryer land areas not suited for crop production (Youngs and Somerville, 2012). At present, the precise response of switchgrass to water scarcity at its roots has been understudied. However, we do know that exposure to water stressed conditions reduces yields (Yi et al., 2012) and that seven weeks of drought conditions significantly diminishes harvestable yields (Barney et al., 2009). The theoretical benefit of the modified plant currently being developed for drought tolerance is that it can maintain the same yield while receiving the same amount of precipitation overall, but has the added advantage that it can withstand intermittent periods of drought where other varieties cannot. This paper investigates the potential land areas in the United States that might be able to sustain this crop.

For this reason, a new drought index was developed for the present analysis because existing indices deal with time periods too long for switchgrass growth or focus only on informing irrigation management decisions. For example, the most widely used drought indices, including the Palmer Drought Index (Alley, 1984) and the Koppen climate classifications (Peel et al., 2007), are most effective in quantifying the severity of long-term droughts on the scale of months or years. Another technique capable of shorter time-scales, the Crop Water Stress Indicator, measures the amount of transpiration based on plant leaf temperatures to inform farmers when irrigation is required to maintain crop yields, but cannot be used to derive the length of dry spells in the past (Jackson et al., 1981). The Water Deficit Index and other remote sensing-based techniques estimate crop water deficits based on inferred sensing and measurements of surface air temperatures (Gu et al., 2007; Moran et al., 1994). However, these methods are meant for irrigation intervention and do not enable quantification of the severity of past droughts. For these reasons, we developed a specialized dryness index using high resolution (spatial & temporal) weather and soil data to provide a measure of dry spell severity for switchgrass, which is then combined with the results of the fuzzy spatial suitability model to quantify available land area within varying dryness thresholds.

The objectives of this paper are to: (1) develop a suitability map for switchgrass in the conterminous United States based on modeled potential yields, land value and land availability; (2) evaluate model sensitivity to fuzzy overlay techniques to identify target area for dryness study; and (3) develop a spatially explicit dryness index for the study area and calculate maximum land area within dryness thresholds.

2. Methods

2.1. National suitability model

2.1.1. Primary suitability criteria

The following variables were identified as primary suitability criteria for the explicit purpose of targeting the most fitting areas to plant drought-tolerant switchgrass.

First, modeled switchgrass yield data (resolution 400 m) were available from Wullschleger and colleagues for a combination of