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Fuzzy GIS-based multi-criteria evaluation for US *Agave* production as a bioenergy feedstock

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Abstract

In the United States, renewable energy mandates calling for increased production of cellulosic biofuels will require a diversity of bioenergy feedstocks to meet growing demands. Within the suite of potential energy crops, plants within the genus *Agave* promise to be a productive feedstock in hot and arid regions. The potential distributions of *Agave tequilana* and *Agave deserti* in the United States were evaluated based on plant growth parameters identified in an extensive literature review. A geospatial suitability model rooted in fuzzy logic was developed that utilized a suite of biophysical criteria to optimize ideal geographic locations for this new crop, and several suitability scenarios were tested for each species. The results of this spatially explicit suitability model suggest that there is potential for *Agave* to be grown as an energy feedstock in the southwestern region of the United States – particularly in Arizona, California, and Texas – and a significant portion of these areas are proximate to existing transportation infrastructure. Both *Agave* species showed the highest state-level renewable energy benefit in Arizona, where agave plants have the potential to contribute 4.8–9.6% of the states' ethanol consumption, and 2.5–4.9% of its electricity consumption, for *A. deserti* and *A. tequilana*, respectively. This analysis supports the feasibility of *Agave* as a complementary bioenergy feedstock that can be grown in areas too harsh for conventional energy feedstocks.

Keywords: *Agave*, bioenergy, biofuel, fuzzy logic, geographic information systems, suitability mapping

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Introduction

Increasing global energy demand, coupled with a changing global climate, necessitates a search for alternatives to energy production that promote environmental and economic sustainability. To this end, there has been substantial interest in the development of renewable bioenergy feedstocks. However, one significant obstacle facing these demands is land availability. To avoid conflicts with existing food production and to minimize use of water and other resources, effective biofuel production will rely on a diversity of bioenergy species, including feedstocks that may be both productive and sustainable on semiarid lands, thereby providing both economic and environmental benefits without impacting food production (Perlack & Stokes, 2011).

Species within the plant genus *Agave* have recently attracted attention as a potential complement to other bioenergy feedstocks (Somerville *et al*., 2010; Davis *et al*., 2011; Holtum *et al*., 2011). Native to the hot, semiarid regions of Mexico and the Southwestern United States, *Agave* spp. are naturally adapted to regions where conventional agricultural production is challenging, if not impossible. As perennial evergreen xerophytes, *Agave* spp. are capable of surviving in areas that experience long dry spells between rain events. The ability of *Agave* spp. to withstand such conditions is in large part due to their use of crassulacean acid metabolism (CAM) – a specialized form of photosynthesis, which allows the plant to keep leaf stomata closed during the hot day, thereby minimizing water loss through evapotranspiration and allowing them to achieve remarkable heat tolerance and water use efficiency (WUE) (Nobel *et al*., 1992). This is in contrast to C_4 feedstocks, like switchgrass and *Miscanthus*, which have a WUE that limits them to areas with relatively high annual rainfall. Even in these extreme environments, and with few nitrogen (fertilizer) inputs, agave plants produce yields comparable to other second-generation bioenergy feedstocks (Somerville *et al*., 2010; Davis *et al*., 2011).

Around the globe, commercial production of agave plants for the manufacturing of both fiber and tequila has been occurring for decades, and agronomic practices

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are well established (Somerville *et al*., 2010). This existing knowledge of the production chain makes commercial production of agave plants for bioenergy even more feasible from an economic perspective. Yan *et al.* (2011) conducted a life-cycle analysis and showed that *Agave* is likely to outperform corn and switchgrass in terms of ethanol output and net greenhouse gas emissions per unit land area. As such, *Agave* spp. represent a new opportunity for arid lands to be utilized for biofuel production. Although *Agave* spp. also grow well in areas with abundant rainfall and good soil water retention, in considering where to plant these species as a biofuel feedstock it is important to prioritize areas where limited rainfall prevents conventional agriculture (Davis *et al*., 2011). To quantitatively scale the potential opportunity of *Agave* spp. as a feedstock and to minimize environmental and economic impacts, there is a need to determine the geographic potential for agave plantations with spatially explicit methods.

Geographic information systems (GIS) is a powerful tool for spatial suitability analyses involving numerous input datasets (Caver, 1991; Jankowski, 1995). GIS-based site suitability analyses are increasingly used to identify potential locations for integrating renewable energies into the landscape (Voivontas *et al*., 1998; Angelis-Dimakis *et al*., 2011). The majority of these analyses are based in multi-criteria evaluation (MCE), the underlying principal of which is to synthesize complex problems with multiple variables. GIS-based MCE analyses traditionally rely on two main approaches: Boolean overlay or weighted linear combination (WLC) (Malczewski, 2004). Boolean overlays consist simply of true and false designations given a specified threshold; an area is either suitable or it isn't. In WLC, weights are attributed to criteria according to the importance of each variable in defining the optimal solution. Both methods employ discrete thresholds to delineate suitability and are usually defined by the opinion of a panel of anonymous experts (Jiang & Eastman, 2000). There are inherently many assumptions in these models, and the association between empirical data and land suitability is often lacking. In addition, sensitivity analyses are not often performed nor are uncertainties about the results even addressed.

In contrast, fuzzy logic, as introduced by Zadeh (1965), allows for more flexibility in analyses where the boundaries between suitable and non suitable are uncertain. The concept of fuzzy set theory involves classes with continuous grades of membership ranging from 0 to 1, with 0 representing the absolute falsehood and 1 being the absolute truth. In the case of suitability analyses, a value of 1 translates to an absolute truth that an area is suitable, values between 0 and 1 have a partial membership of suitability, and a value of 0 translates to a complete falsehood that an area is suitable.

A common argument within the literature is that fuzzy models allow for the inclusion of uncertainty in expert opinion and address continuous environmental factors that are not easily represented by discrete thresholds (Jiang & Eastman, 2000). However, even in fuzzy models, expert decision makers still determine minimum and maximum input parameters, i.e., the 1's and 0's, which may impact the final mapped results. Because overlay functions within fuzzy models are often multiplicative, any input criterion with a 0 value immediately casts that location as unsuitable – despite the presence of several other suitable factors at that same location. The sensitivity of these models in regards to spatial suitability mapping has not been explored.

In addition to finding a suitable location, one of the biggest monetary expenses in the bioenergy production chain is transportation costs. Therefore, proximity to infrastructure is essential to make biofuel projects economically sustainable. The costs and environmental impacts are substantially higher for road transport than for rail or ship, thus railroad networks are the most economically efficient mode of land transportation for bulk cargo [4]. However, rail network density in the west is much sparser than in the east where biofuel feedstocks like *Miscanthus* are being targeted. In the case of agave plants, which can grow in marginal areas not currently being utilized by crop production, there may be gaps in the network where production potential is limited by distance to infrastructure.

To date, the geographic potential for *Agave* as a biofuel feedstock in the United States is not known. To explore this concept, we (i) develop a multi-criteria land suitability model based on fuzzy logic to site potential areas for two *Agave* species, *Agave deserti* and *Agave tequilana*, to be grown as biofuel feedstocks; (ii) test the sensitivity of this model to small changes in input parameters; (iii) construct multiple suitability scenarios adjusting input parameters to be more strict or optimistic based on extremes available in the empirical data; (iv) integrate model results with existing transportation infrastructure to see where agave may be optimized in the landscape both physically and economically.

Materials and methods

Species selection

Two target species were identified for this study: *Agave tequilana and Agave deserti*. *A. tequilana* is a species with known commercial-scale operations and is well documented to produce high yields (24 Mg ha^{-1} yr^{-1}) with limited inputs (Nobel & Valenzuela, 1987). The species has considerable photosynthetic plasticity in response to changes in temperature, light, and water in addition to an ability to sequester a great amount of carbon (Pimienta-Barrios *et al*., 2001). The second species reviewed here, *A. deserti,* is native to California and southwestern Arizona. It produces comparatively limited yields (7 Mg ha^{-1} yr^{-1}) but is native to very arid climates and represents one extreme of the thermotolerance and drought tolerance spectrum of the *Agave* genus (Nobel & Hartsock, 1986). In addition to having a high tolerance to extreme heat, *A. deserti* also has a relative tolerance to cold temperatures – especially as compared to other *Agave* species.

Based on potential yield *A. tequilana* is the more likely crop of the two to be used for bioenergy purposes and may also be a better proxy for other high-yielding *Agave* species. In contrast, *A. deserti* is less productive but shows some desirable characteristics for growing the crop in the United States (e.g., a wide temperature tolerance) and is therefore a useful comparative species to use in the model. These two species are among the most extensively studied in the *Agave* genus, therefore the broad amount of literature makes them ideal test cases to use in this model. While other Agave species currently grown for fiber (e.g., *A. sisalana* and *A. fourcryodes*) may also be potential candidates for bioenergy production, at the time of this publication there is not enough data on physiological responses to environmental stimuli for analysis of additional species in the present model.

Suitability model

For this study, a geospatial suitability model was developed that incorporates fuzzy logic and utilizes a suite of biophysical variables to identify ideal geographic locations for this new crop. The following steps are outlined in Fig. 1.

Selection criteria and data preprocessing

Criteria determining *Agave* growth parameters were identified based on a review of the existing literature, and national-level geospatial datasets best emulating data from empirical studies were collected (Table 1). Data on climate conditions (years 1971–2000), including temperature (min, max) and precipitation were acquired from PRISM 30-arcsec (800 m) (PRISM Climate Group, 2004). STATSGO soils data were acquired from NRCS-USDA General Soil Map (STATSGO2), including percent sand, percent clay, percent silt, pH, and bulk density (1 : 250 000) (Miller & White, 1998). Solar data on direct normal irradiance (DNI) were acquired from SUNY Albany and NREL (0.1 dd × 0.1 dd) (Perez *et al*., 2002). Topography data (percent slope) from the HYDRO1k dataset were acquired from USGS/EROS (1 km) (USGS, 1996).

Prior to model implementation, some additional preprocessing of the data was necessary to determine the best fit of the empirical data used to parameterize the model. First, soils data were estimated as the depth-weighted average in the top 20 cm of soil – Layers (*L*) 1–3 derived from the STATSGO dataset Eqn (1). This depth was chosen based on available field samples (Gobeille et al., 2006; Nobel & Valenzuela, 1987).

$$\text{depth-weighted average} = \frac{L_1 * \text{Depth}_1 + L_2 * \text{Depth}_2 + L_3 * \text{Depth}_3}{\text{Depth}_1 + \text{Depth}_2 + \text{Depth}_3};$$
$$\text{where Depth}_1 = 5\ (0-5cm);$$
$$\text{Depth} = 5\ (5-10cm);$$
$$\text{Depth}_3 = 10\ (10-20cm) \quad (1)$$

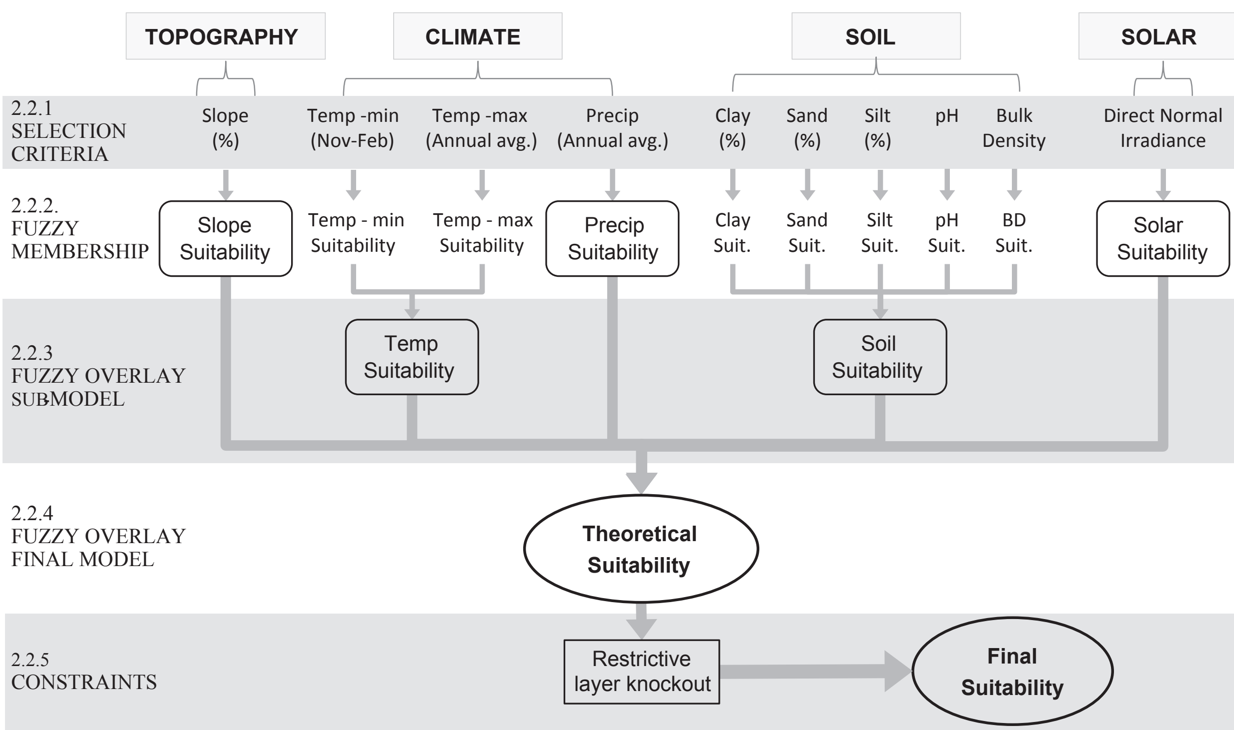

Fig. 1 The famework for the suitability model incorporates fuzzy logic modeling in both the membership and overlay processes.

Table 1 General description of the research data

	Data	Source	Resolution	Description	Citation
Climate	*Tmin*	PRISM	30 arcsec (ca. 800 m)	US Average for Annual Minimum Temperature, 1971–2000	(PRISM Climate Group, 2004)
	Tmax			US Average for Annual Maximum Temperature, 1971–2000	
	Precip			US Average for Annual Precipitation, 1971–2000	
Soil	*Bulk Density*	CONUS - STATSGO - USGS NRCS	1 : 250 000 (mmu ca. 2.3 mi^2)	Bulk density is the ratio of the mass of soil to its total volume (solids and pores together)	(Miller & White, 1998)
	Clay%			Proportion of clay in the soil	
	Silt%			Proportion of silt in the soil	
	Sand%			Proportion of sand in the soil	
	pH			pH is a measure of the acidity or alkalinity of the soil	
Topography	*Slope*	HYDRO1k - USGS/EROS	1 km = 1000 m	Maximum change in the elevations between each cell and its eight neighbors. The slope is expressed in integer degrees of slope between 0 and 90	(USGS, 1996)
Solar	*Direct Normal Irradiation*	SUNY Albany and NREL	0.1 × 0.1 dd (ca. 10 km)	Annual average solar resource potential; data is shown in watt hours per meter squared per day	(Perez *et al*., 2002)

Second, monthly minimum temperature data for the months of November through February were combined to estimate the absolute minimum temperature during those months. Finally, all data were reprojected to NAD83 with appropriate datum transformations and then resized to match the extent & cell size of the PRISM grids (30 arcsec).

Fuzzy membership transformations

Raw data of the input suitability criteria were transformed into standardized suitability criteria by process of fuzzy transformation functions, which convert raw values (x-axis) into 'fuzzy' values (0–1) (y-axis). A membership function expresses the degree of membership between 0 and 1.

Figure 2 illustrates an example of a trapezoidal shaped fuzzy membership transformation function used for the majority of the suitability criteria in this study (Pedrycz, 1994). This function assigns linear grades of membership Eqn (2):

$$\mu(x) = 0 \text{ if } x < \text{min}, \mu(x) = 1 \text{ if } x > \text{max}, \quad \text{Otherwise}, \mu(x) = \frac{(x - \text{min})}{(\text{max - min})} \tag{2}$$

Minimum and maximum input parameters were based on empirical information in the published literature. For *A. tequilana* suitable soil physical properties were determined from the work of Nobel and Valenzuela (Nobel & Valenzuela, 1987) as well as Gobeille *et al.* (Gobeille *et al*., 2006). Optimum temperatures for *A. tequilana* were determined from the work of Ruiz-Corral *et al*., (2002), Cedeño, (1995), and Pimienta (Pimienta-Barrios *et al*., 2001). The parameters for precipitation were determined from the work of Cedeño. For *A. deserti*, suitable soil physical properties were acquired from the work of Young and Nobel (Young & Nobel, 1986). Remaining criteria for *A. deserti* were acquired from the Agave Hill research center (Riverside County, CA; Lat/Long: 33.6386, −116.3983, elevation = 833 m) for weather data collected between March 1973 and November 2011.

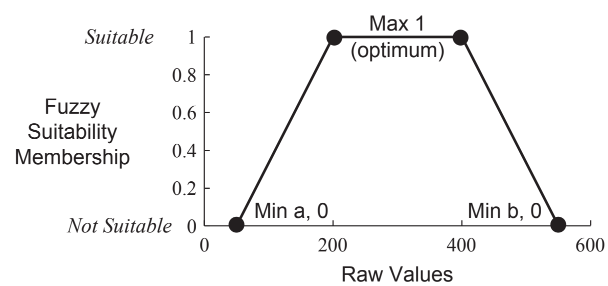

Fig. 2 Fuzzy membership transformation functions used for the majority of the suitability criteria in this study transforms raw values of the input criteria to degrees of membership between 0 and 1.

Nonlinear membership functions were applied to two suitability criteria: slope and solar radiation. The Large function, which creates a sigmoid shape where large values have high membership Eqn (3), was used for the solar radiation criterion, as higher solar energy for *Agave* has a positive influence on yield (Ruiz-Corral *et al*., 2002). For this study, we applied a midpoint of 3.5 and a spread of 10.

$$\mu(x) = \frac{1}{1 + \frac{x - f_1}{f_2}} \text{ where } f_1 \text{ is the spread and } f_2 \text{ is the midpoint.} \tag{3}$$

The Small function, which creates a sigmoid shape where small values have high membership Eqn (4), was used for the slope criterion, as we assumed commercial feedstock production becomes less and less suitable as the percent slope increases. For this study, we applied a midpoint of 5 and a spread of 3.

$$\mu(x) = \frac{1}{1 + \frac{x f_1}{f_2}} \text{ where } f_1 \text{ is the spread and } f_2 \text{ is the midpoint.} \tag{4}$$

Fuzzy overlay submodel

Prior to the final overlay, it was necessary to first combine standardized suitability criteria within like-classes (soil and temperature criteria) to create categorical standardized suitability criteria. This was done using a fuzzy overlay function. The overlay function 'Gamma' multiplies the fuzzy sum by the fuzzy product to the power of gamma (Eqn 7). At high values of gamma, the Gamma function is dominated by the fuzzy algebraic sum and is additive in character; that is, favorable input values result in an output that is larger than any of the inputs. A gamma of 1 is closer to the fuzzy sum (Eqn 5), whereas a gamma value approaching 0 is closer to the fuzzy product (Eqn 6). See equations below.

$$\text{Fuzzy Sum Value} = 1 - \text{product}(1 - \text{arg}_1, \ldots, 1 - \text{arg}_n) \tag{5}$$

$$\text{Fuzzy Product Value} = \text{product}(\text{arg}_1, \ldots, \text{arg}_n) \tag{6}$$

$$\text{Fuzzy Gamma Value} = (\text{Fuzzy Sum})\gamma * (\text{Fuzzy Product})1 - \gamma \tag{7}$$

The five standardized soils criteria (pH, bulk density, and percent clay, sand, and silt) were combined into a single standardized soil suitability criterion using a Gamma fuzzy overlay function with a gamma value of 0.9. The standardized suitability criteria for temperature minimum & maximum were also combined using the Gamma overlay function with a gamma value 0.9 into one final standardized temperature suitability criterion.

Fuzzy overlay final model

All five final standardized suitability criteria, including slope, temperature, precipitation, soil, and solar, were combined into a final suitability map using a fuzzy overlay approach. A Gamma fuzzy overlay function was used with a gamma value of 0.9. This resulted in values ranging from 1 to 0, with 1 being most suitable, and 0 being least suitable.

Constraints

Finally, land uses considered inappropriate for planting biofuels for physical, economic, or environmental reasons were also identified and removed from further analysis. The 2012 Cropland Data Layer was used to identify areas of existing cropland, forest land, urban areas, water, snow/ice, and wetlands (Boryan *et al*., 2011). Urban areas and military installations available from the 2012 TIGER/Line Census were also excluded. These include boundaries of military installations from the US Department of Defense for Air Force, Army, Marine, and Navy installations and from the US Department of Homeland Security for Coast Guard installation. In addition, the national Protected Areas Database (PAD-US v1.2) was used to identify areas of protected lands based on management intent to conserve biodiversity, as described by GAP Status Codes (USGS GAP (GAP), 2011). GAP lands of Status Code 1 or 2 are permanently protected lands and were considered restrictive layers in this analysis. Lands in GAP Status 3 & 4 are less protected and potentially subject to biofuel production, therefore these lands were not included in the restrictive layers of this study. All restrictive layers were assigned a suitability value of 0 (i.e., non suitable) and combined via linear combination into one masking layer where lands were not considered suitable for planting dedicated perennial grass biofuel crops.

Sensitivity analysis

To examine the sensitivity of the dependent outcome to moderate changes in the input parameters of each independent suitability criteria, a sensitivity analysis was conducted. These analyses were performed by varying the input parameters for the fuzzy membership transformation function of a single criterion while holding the parameters of other criteria fixed. One at a time, the parameters for a single suitability criterion were adjusted to be either 10% higher or 10% lower than the total range of the variable parameters identified in the literature review (Table 2 – original scenario).

Finally, a tornado diagram was constructed to summarize the individual impact of many independent criteria on the mapped results (Eschenbach, 1992). The suitability criteria tested include temperature minimum (tmin), temperature maximum (tmax), precipitation (precip), slope, solar, pH, bulk density, sand, silt, clay, and all soils combined. Each diagram demonstrates the impact of independently varying each of these fuzzy membership parameters. The base-case suitable land area of the moderate (i.e., original) suitability model (100%) defines the vertical axis of the diagram. From here, changes in percent mapped suitable land area owing to any one independent suitability criteria deviate from the base case.

Scenarios

In addition to the initial suitability model run, additional suitability scenarios were created for the *A. deserti* and *A. tequilana* suitability models, in which input fuzzy membership parameters were adjusted to be more or less restrictive. These parameters were based on physical extremes as observed in the available empirical data (Table 2). In one scenario, input parameters were altered to be more restraining than those in

Table 2 Model input parameters to fuzzy transformation functions

	Moderate (Original)			Optimistic			Strict			
	Min a (0)	Max (1)	Min b (0)	Min a (0)	Max (1)	Min b (0)	Min a (0)	Max (1)	Min b (0)	Reference
A. deserti										
pH	3	6.3–8.1	9.1	3	6.3–8.1	9.1	5	7–8	9	Agave Hill
BD	0	1.451–1.657	2.65	0	1.078–1.657	2.65	0	1.078–1.657	2.65	(Young & Nobel, 1986)
Clay (%)	0	5.75–6.21	70.16	0	5.75–6.21	70.16	–	≤6.21	40	
Sand (%)	0	69.56–81.28	92	0	≥40	–	40	69.56–81.28	92	
Silt (%)	0	16.29–18.37	82	0	16.29–18.37	82	0	16.29–18.37	82	
tMin °C	0	≥5	–	0.1	≥4.4	–	≤4	≥8	–	
tMax °C	18.5	22.5–27.4	29.9	9	13.8–35.1	39.7	18.5	22.5–27.4	29.9	Agave Hill
Precip (mm yr^{-1})	37.8	112.65–357.8	528.1	37.8	112.65–528.1	800	70	192.4–357.8	528.1	
A. tequilana										
pH	3	4.5–6.43	9.1	3	4.5–6.43	9.1	5;9	7–8	9	(Gobeille *et al.*, 2006)
BD	0	0.68–1.54	2.65	0	0.68–1.54	2.65	0	0.68–1.54	2.65	(Nobel & Valenzuela, 1987)
Clay (%)	0	≥37.94	–	0	≥37.94	–	0	40–70	100	
Sand (%)	0	12.72–40.53	92	0	≥40	–	0	12.72–40.53	92	
Silt (%)	–	–	–	–	–	–	–	–	–	–
tMin °C	≤0.1	≥5	–	≤0.1	≥4.4	–	≤4	≥8	–	(Ruiz–Corral *et al.*, 2002)
tMax °C	10	15–25	33	10	15–35	40	10	15–25	33	
Precip (mm yr^{-1})	250	500–1000	1200	250	500–1000	1200	600	800–1000	1200	(Cedeño, 1995)

the original (termed the 'strict' model). In another scenario, input parameters were altered to be more liberal than those in the original model (termed the 'optimistic' model). As such, the original model represents a 'moderate' scenario and will be referred to as such throughout the remainder of the article. Not all parameters were adjusted for each scenario; solar radiation and slope remained unchanged for all scenarios. Table 2 displays the final parameters used.

Steps 2.2.2 through 2.2.5 in Fig. 1 were repeated for each of the six scenarios in the sensitivity analysis, resulting in six mapped suitability results with values ranging from 1 to 0. To aid comparison between scenarios, based on the distribution of continuous suitability measure, suitable values were aggregated into four suitability classes: very suitable (VS) (1, 0.95), suitable (S) (0.95, 0.85), moderately suitable (MS) (0.85–0.01), and non suitable (NS) (0).

Infrastructure

Finally, the North American CTA Railroad Network (Peterson, 2012) was used to assess the proximity of the potential agave resources to existing infrastructure. This operational freight network only contains current operators and has a geographic accuracy of 100 m. A buffering methodology that screens for regions surrounding active railroad nodes was utilized at distances of 25 km and 50 km. Areas of suitable land falling both within and outside of the designed buffers were calculated.

Energy estimates

To estimate potential agave-derived ethanol production and energy requirements, including potential excess electricity that could be exported to the electric grid, first generation biofuels conversion assumptions were used. Recent US corn ethanol conversion efficiencies were used to estimate the energy requirements for agave-based biorefineries (Perrin *et al.*, 2009). Davis *et al.*, (2011) observed that approximately 1 l of 40% ethanol is produced from 5.5 kg of dry agave biomass in modern large-scale tequila production facilities in Mexico. For simplification, here it was assumed that the sugar from the piña is the feedstock for fermentation into ethanol with the conversion efficiency observed by Davis *et al.*, (2011) and that both the bagasse (remaining solids from the piña after sugar extraction) as well as the harvested agave leaves are utilized in a combined heat and power (CHP) unit in the biorefinery. Although bagasse and harvested agave leaves could be used in other power generation settings, for this analysis it was assumed that an onsite CHP unit would provide the biorefinery process heat and electricity and that excess energy would be converted and supplied to the electric grid. It could be argued that the leaves of harvested agave plants should be returned to the soils for nutrients replenishment, however, here we assumed that all of the harvested agave is utilized for energy production (as ethanol, heat, and power). Ethanol potential, energy consumption at biorefineries, and excess electricity supplied to the electric grid were calculated for *A. deserti* and *A. tequilana*, respectively.

Results

Suitability model results

The *A. deserti* suitability model results show California, Arizona, and Texas as potentially suitable areas for planting *Agave* as a biofuel feedstock (Fig. 3). Results for the *A. tequilana* suitability model highlight Texas as a very suitable region in part because it has minimum land cover constraints. California and Arizona also show a substantial amount of suitable area, however, they have significantly less area than Texas. Employing model constraints reduced and fragmented many of the potentially suitable land areas in California, particularly the Central Valley, which is dominated by cropland, along with the urbanized areas of Los Angeles and San Diego Counties. Large land tracts in Arizona remained less fragmented. Still, overall mapped suitable land area remained higher in California.

Looking at the current land cover in the three states with the most mapped suitable land area, in Arizona over 95% of the potentially suitable area is shrub land. Shrub land is also a significant land cover in the suitable areas of California (ca. 40%) and Texas (ca. 50%), but in these states grassland is also a substantial land cover within potentially suitable areas (ca. 45% in California and ca. 13% in Texas). This analysis does not, however, exclude pasture and grazing land. Texas was the only state to show pastureland in the suitable area, where ca. 20% of the land suitable area for *A. tequilana* is classified as pasture/hay.

Sensitivity analysis results

For both *A. tequilana* and *A. deserti*, adjusting the minimum temperature range had the greatest effect on suitable land area mapped as suitable (Fig. 4a and b). Decreasing the minimum optimum temperature increased the mapped suitable area by 76% in the case of *A. tequilana* and 40% in the case of *A. deserti*. Changing temperature maximum has little effect on mapped suitable land area for *A. tequilana*; however, for *A. deserti*, increasing the optimum temperature maximum 10% of the range (1 °C) increases the mapped suitable land area by 12.7%. The effect of adjusting optimal precipitation has opposite effects on *A. tequilana* and *A. deserti*. For *A. deserti,* increasing optimal precipitation increased the mapped suitable land area by 19%, whereas for *A. tequilana* – a species which has higher water requirements – decreasing the amount of optimal precipitation increased suitable land area 6%. For *A. deserti* it is clear that climatic criteria, including temperature and precipitation have the biggest impact on mapped results.

As compared to temperature and precipitation, adjusting the fuzzy membership parameters for soil criteria had relatively little influence on area mapped as suitable.

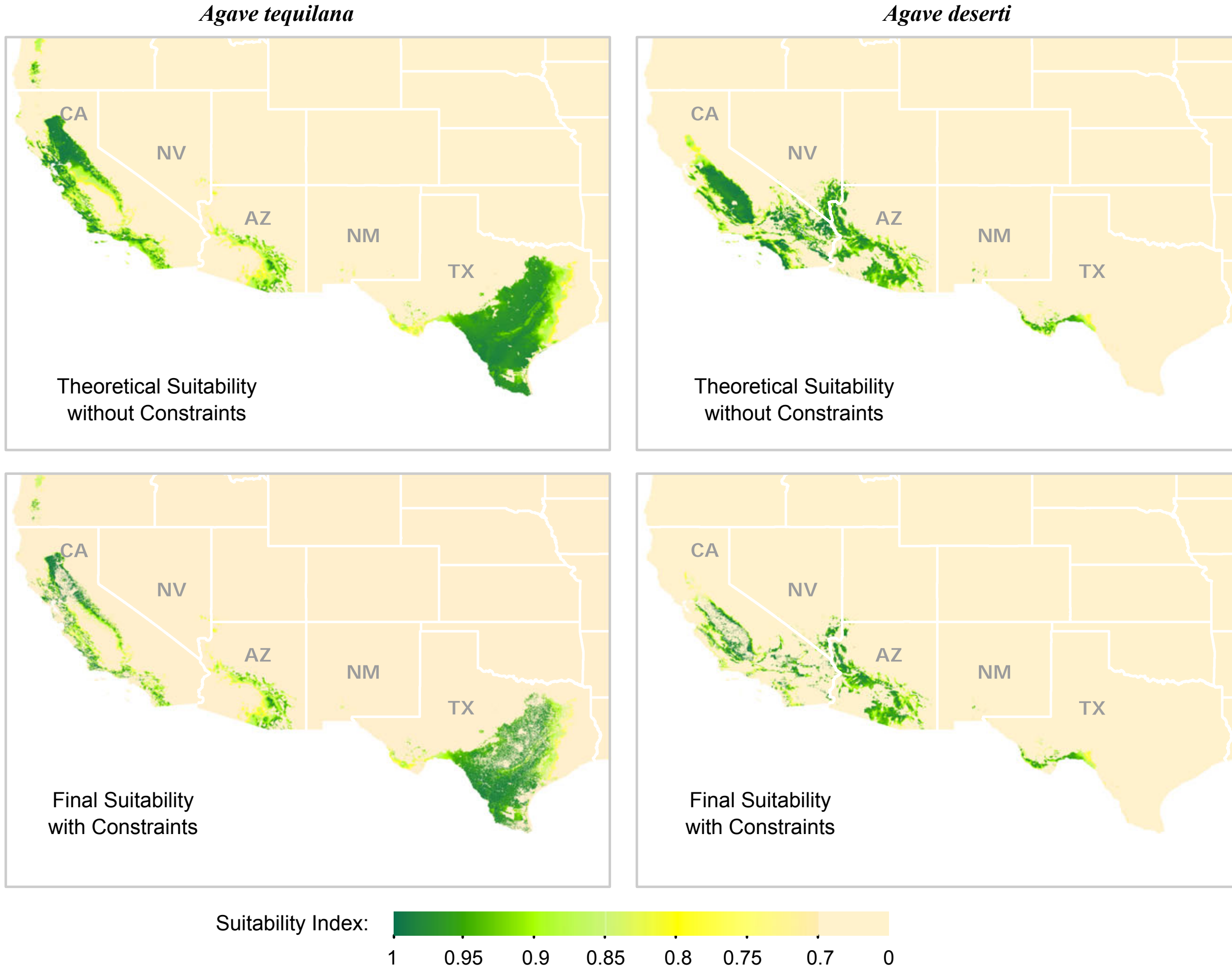

Fig. 3 Results for the *A. deserti* suitability model highlight California, Arizona, and Texas as potentially suitable areas for planting agave plants as a biofuel feedstock.

However, of the soil criteria, percent clay and percent sand had the most influence. For both *A. tequilana* and *A. deserti*, adjusting parameters for slope and solar variables had little influence on mapped results. Increasing the amount of solar radiation required for *A. deserti* reduced the mapped suitable land area by 7%, while the effect of changing the solar radiation input parameter had nearly no detectable effect on *A. tequilana*. Changing the parameters for the slope input criterion had hardly any detectable effect on either species (<1%). Figs 4a and b display combined results for all suitability classes: Moderately Suitable, Suitable, and Very Suitable.

Scenario Results

As compared to the moderate (original) model parameters, both the optimistic and strict suitability scenarios generated increased and decreased mapped suitable land area estimates, respectively (Table 3; Fig. 5). The optimistic parameters for *A. tequilana* increased the suitable area by half (150%) and the strict parameters decreased suitable area to 20% of the moderate scenario. For *A. deserti*, the optimistic scenario nearly doubled the mapped suitable area (197%) and the strict parameters decreased suitable area to 10% of the moderate scenario. In both the optimistic and moderate scenarios, the modeled suitability results for the two species – *A.tequilana* and *A. deserti* showed the most overlap primarily in southern Arizona as well as certain areas in southern California and Texas.

Climatic variables, including temperature (particularly average minimum winter temperature), and precipitation were the most influential suitability criteria in the model. Owing primarily to high precipitation and moderate minimum temperatures in the Pacific Northwest, the optimistic suitability model for *A. tequilana*

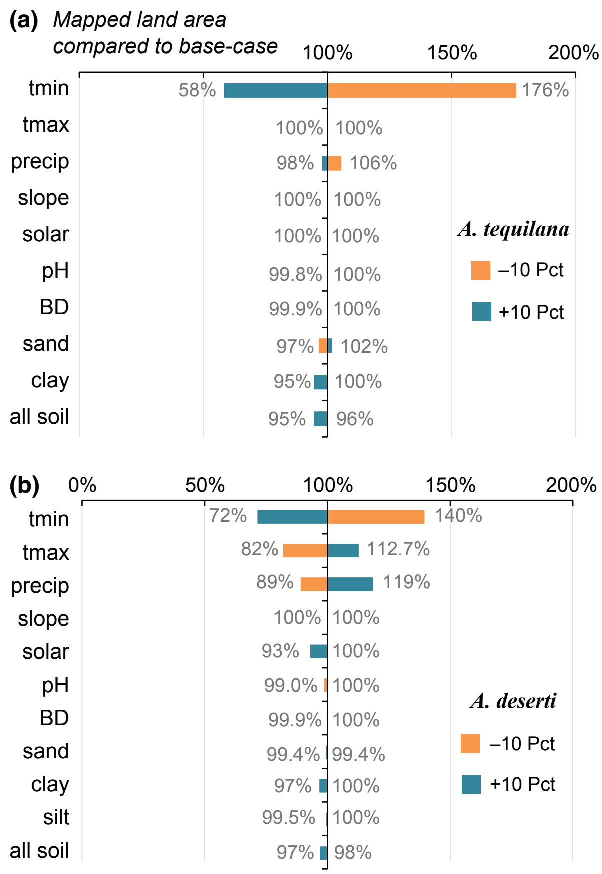

Fig. 4 These tornado diagrams illustrate the impact of varying the parameters of input criteria in the model. The base-case suitable land area of the moderate (original) model (100%) defines the vertical axis; from here, changes in percent mapped suitable land area owing to changes in any one input criterion deviate from the base case.

showed suitability as far north as Oregon and Washington states. Limiting the minimum precipitation parameter from those in the moderate scenario from 250 to 600 mm yr^{-1} in the strict scenario significantly reduced the amount of suitable area to primarily the southwestern region of Texas.

Although mapped suitable area differs considerably among suitability models, under all scenarios the model accurately predicts suitability for *A. deserti* in all counties identified by the Biota of North America Program where *A. deserti* is native and not rare. As these data were not used to drive model inputs, this comparison serves as an independent assessment (Kartesz, 2010). That being said, the mapped suitable areas in the strict scenario are not abundant, which might imply that this scenario is in fact more restrictive than in reality, and that the moderate mapped scenario more realistically depicts the potential distribution of *A. deserti*.

Proximity to infrastructure

Restricting suitable areas to 50- and 25-km buffers around railroad nodes decreased the amount of total suitable area mapped by 92% to <1%, depending on species and scenario (Table 4). For example, as compared to the unrestricted moderate model for *A. tequilana* (28.2 Mha), suitable land constrained to the 50 km buffer was reduced to 25.2 Mha – a difference in mapped land area of 11%. When restricted to a 25 km buffer, the original land area mapped as suitable for *A. tequilana* in the moderate scenario was reduced to 17.2 Mha – a 39% decrease. In the optimistic scenario, the suitable land area mapped decreased by 7% for the 50 km buffer and to 46% for the 25 km buffer. In the strict scenario, suitable areas only decreased by <1% for the 50 km buffer, and <7% for the 25 km buffer. Higher reductions were seen for the optimistic scenario because more land area was mapped as suitable.

For *A. deserti*, the original land area mapped as suitable in the moderate scenario (13.13 Mha) decreased 14% (11.26 Mha) when restricted to a 50 km buffer, and 48% (6.86 Mha) when restricted to the 25 km buffer. For the optimistic scenario, the suitable land area mapped decreased by 26% for the 50 km buffer and to 92% for the 25 km buffer. In the strict scenario, suitable areas only decreased by 1% for the 50 km buffer, and 4% for the 25 km buffer.

At the state level, when the mapped suitable land area for *A. tequilana* was restricted to land areas within the 25 km infrastructure buffer, the majority of the orig-

Table 3 Estimated land available for *A. tequilana* and *A. deserti*, depending on model scenario

Totals (Mha)						Totals (Mha)					
A. tequilana	VS	S	MS	Total	% Orig.	*A. deserti*	VS	S	MS	Total	% Orig.
Optimistic	17.82	19.91	4.76	42.49	150.7%	Optimistic	15.82	7.23	2.88	25.92	197.5%
Moderate	13.56	8.97	5.67	28.20	100.0%	Moderate	5.11	5.80	2.22	13.13	100.0%
Strict	0.00	1.46	4.23	5.69	20.2%	Strict	0.02	0.47	0.84	1.33	10.1%

VS, very suitable; S, suitable; MS, moderately suitable land areas sum to the total estimated suitable land area.

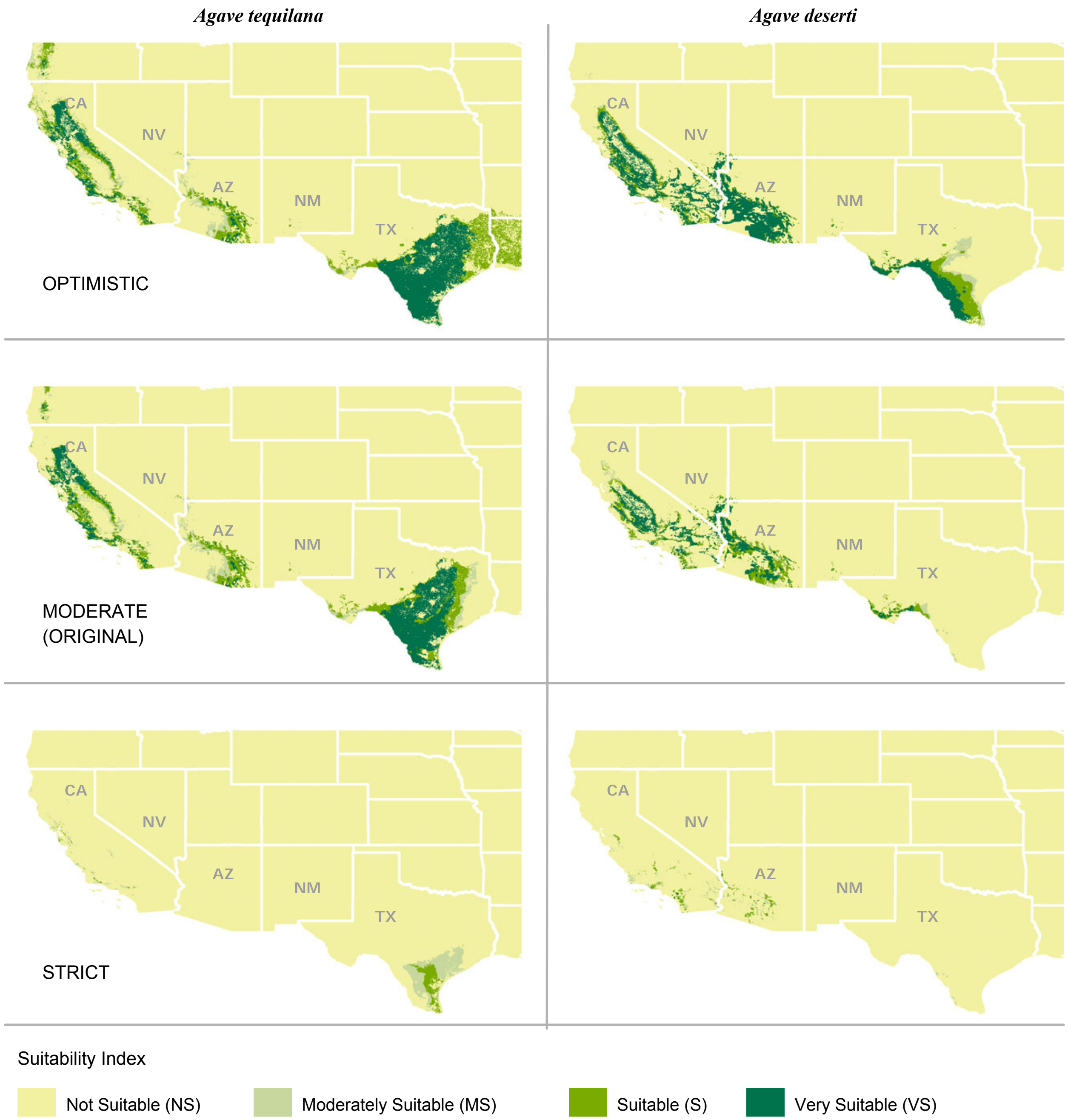

Fig. 5 For both *A. tequilana* and *A. deserti*, California, Texas, and Arizona are highly suitable. Both the optimistic and strict suitability scenarios generate increased and decreased mapped suitable land area estimates, respectively.

inally mapped suitable land areas in the moderate scenario (15.58 Mha out of 17.20 Mha) occurred within Texas (9.99 Mha), California (3.65 Mha), and Arizona (1.94) (Table 5). However, while in both the moderate and optimistic scenarios, California and Arizona have a substantial amount of land potentially suitable for *A. tequilana* (4.61 Mha and 1.94 Mha in the optimistic scenario, respectively), in the strictest scenario, nearly all suitable land area for *A. tequilana* is limited to Texas (3.47 Mha within the 25 km buffer and 5.23 Mha within the 50 km buffer).

The results for *A. deserti* at the state-level show that the majority of the originally mapped suitable land areas in the moderate scenario was restricted to the 25 km infrastructure buffer area (6.44 Mha out of 6.86 Mha) within California (3.56 Mha), Arizona

Table 4 Estimated land available within buffers around railroad nodes, depending on species and scenario

A. tequilana	VS	S	MS	Total	% ORIG	*A. deserti*	VS	S	MS	Total	% ORIG
Totals, Mha (50 km buffer)						Totals, Mha (50 km buffer)					
Optimistic	17.82	19.05	3.68	40.55	143.78%	Optimistic	13.82	6.24	2.46	22.52	171.59%
Moderate	12.39	8.12	4.68	25.19	89.31%	Moderate	4.62	4.68	1.96	11.26	85.76%
Strict	0.00	1.43	4.08	5.52	19.56%	Strict	0.02	0.41	0.76	1.19	9.06%
A. tequilana	VS	S	MS	Total	% ORIG	*A. deserti*	VS	S	MS	Total	% ORIG
Totals, Mha (25 km buffer)						Totals, Mha (25 km buffer)					
Optimistic	11.45	15.75	2.28	29.48	104.52%	Optimistic	8.70	3.60	1.53	13.82	105.30%
Moderate	8.42	5.60	3.18	17.20	61.00%	Moderate	2.89	2.74	1.23	6.86	52.25%
Strict	0.00	0.93	2.77	3.70	13.13%	Strict	0.02	0.27	0.51	0.80	6.11%

VS, very suitable; S, suitable; MS, moderately suitable land areas sum to the total estimated suitable land area.

Table 5 State-level results for land area mapped as suitable within the 25- and 50 km buffers

	25 km buffer (Mha)			50 km buffer (Mha)		
	Optimistic	Moderate	Strict	Optimistic	Moderate	Strict
A. tequilana						
California	4.61	3.65	0.24	6.62	6.28	0.29
Arizona	1.94	1.94	0.00	3.47	3.47	0.00
Texas	11.63	9.99	3.47	16.54	14.50	5.23
A. deserti						
California	5.66	3.56	0.49	8.05	5.09	0.61
Arizona	3.37	2.27	0.30	5.92	4.38	0.53
Texas	4.35	0.61	0.01	7.96	1.22	0.04

(2.27 Mha) and Texas (0.61 Mha) (Table 5). In the optimistic scenario, Texas shows more mapped suitable land area than Arizona (4.35 Mha compared to 3.37 Mha, respectively). However, with more strict parameters employed, only California and Arizona remain as suitable areas (0.49 and 0.30 Mha, respectively) and the suitable land in Texas drops to 0.01 Mha.

Yield estimates

Assuming yields of 24 Mg ha^{-1} yr^{-1} for *A tequilana* (Nobel & Valenzuela, 1987) and 7 Mg ha^{-1} yr^{-1} for *A. deserti* (Nobel & Hartsock, 1986) and additional conversion and production assumptions outlined above, Tables 6 and 7 estimate the ethanol potential, energy consumption at biorefineries, and excess electricity supplied to the electric grid for *A. tequilana* and *A. deserti*, respectively. The share of ethanol production, and consequently electricity and fuel consumption and exported electricity between states are also presented in Tables 6 and 7.

Based on the original mapped suitable land area for *A. tequilana* in the moderate scenario within the 50 km transportation buffer, there is a production potential of 8793 Ml of ethanol, an electricity consumption of 1324 GWh, a fuel consumption of 64 454 TJ, and an exported electricity potential of 26 370 GWh (Table 6). The results for *A. deserti*, in the moderate scenario within the 50 km buffer show a production potential 1146 Ml of ethanol, an electricity consumption of 173 GWh, a fuel consumption of 8401 TJ, and an exported electricity potential of 3437 GWh (Table 7). Considering that in 2012, the United States produced 13 300 million gallons of ethanol (50 346 Ml) (Renewable Fuels Association, 2013), these numbers for *A. tequilana* calculate out to 28.1% of total US production in the optimistic scenario within 50 km of rail infrastructure, 17.5% in the moderate scenario, and 3.8% in the strict scenario.

The state-level results follow the trend of mapped suitable land area. For *A. tequilana*, in the strictest scenario, potential suitability is limited only to Texas, while California and Arizona are also significant contributors in moderate and optimistic scenarios. The reverse is seen for *A. deserti*. In the optimistic scenario, Texas joins California and Arizona as a potentially significant contributor of ethanol and energy from *A. deserti*, but in the moderate and strict models, production is limited to California and Arizona.

Table 6 State-level potential energy impacts for *A. tequilana*

A. tequilana		Transportation Buffer 50 km (25 km)			
Region	Scenario	Ethanol Ml*	Electricity Consumption (GWh)†	NG Consumption (JT)‡	Exported Electricity (GWh)§
Total	Optimistic	14 156 (10 291)	2132 (1550)	103 767 (75 432)	42 454 (30 861)
	Moderate	8793 (6005)	1324 (904)	64 454 (44 020)	26 370 (18 010)
	Strict	1926 (1293)	290 (195)	14 118 (9475)	5776 (3876)
California	Optimistic		16% (16%)		
	Moderate		25% (21%)		
	Strict		5% (6%)		
Arizona	Optimistic		9% (7%)		
	Moderate		14% (11%)		
	Strict		<1% (<1%)		
Texas	Optimistic		41% (39%)		
	Moderate		58% (58%)		
	Strict		95% (94%)		

*Assumes 1 l of 40% ethanol per 5.5 kg of dry agave biomass.
†Assumes 0.151 kWh l^{-1}.
‡Assumes 7.33 MJ l^{-1}.
§Assumes 4.324 j g^{-1} of total harvested agave biomass is available to the combined heat and power (CHP) with a 60% boiler efficiency and 40% Rankine cycle efficiency for conversion into electricity. Thermal energy from the CHP first supplies necessary thermal energy to the biorefinery and excess energy is converted to electricity. Biorefinery electricity demand is satisfied and the remainder is exported to the electric grid.

Table 7 State-level potential energy impacts for *A. deserti*

A. deserti		Transportation Buffer 50 km (25 km)			
Region	Scenario	Ethanol Ml*	Electricity Consumption (GWh)†	Fuel Consumption (TJ)‡	Exported Electricity (GWh)§
Total	Optimistic	2293 (1407)	345 (212)	16 809 (10,315)	6877 (4220)
	Moderate	1146 (698)	173 (105)	8401 (5,118)	3437 (2094)
	Strict	121 (82)	18 (12)	887 (598)	363 (245)
California	Optimistic		36% (41%)		
	Moderate		45% (52%)		
	Strict		51% (61%)		
Arizona	Optimistic		26% (24%)		
	Moderate		39% (33%)		
	Strict		44% (37%)		
Texas	Optimistic		35% (31%)		
	Moderate		11% (9%)		
	Strict		3% (1%)		

*Assumes 1 l of 40% ethanol per 5.5 kg of dry agave biomass.
†Assumes 0.151 kWh l^{-1}.
‡Assumes 7.33 MJ l^{-1}.
§Assumes 4.324 j g^{-1} of total harvested agave biomass is available to the combined heat and power (CHP) with a 60% boiler efficiency and 40% Rankine cycle efficiency for conversion into electricity. Thermal energy from the CHP first supplies necessary thermal energy to the biorefinery and excess energy is converted to electricity. Biorefinery electricity demand is satisfied and the remainder is exported to the electric grid.

State-level demands for renewable fuels & electricity

In addition to United States federal mandates such as the Renewable Fuels Standard, state-specific transportation fuels programs and renewable portfolio standards for electricity promote the development and use of renewable energy. For this reason, the yield results estimated here were compared with specific state transportation fuel and electricity demands. Table 8 shows the relative contribution that agave-based biofuels and

Table 8 Potential state-level energy benefit from producing agave plants as a bioenergy feedstock

		A. tequilana Transportation Buffer – 50 km (25 km)		*A. deserti* Transportation Buffer – 50 km (25 km)	
Region	Scenario	Ethanol Percent of State 2010 Gasoline Consumption*	Exported Electricity Percent of State 2010 Electricity Consumption†	Ethanol Percent of State 2010 Gasoline Consumption*	Exported Electricity Percent of State 2010 Electricity Consumption†
California	Optimistic	2.8% (2%)	1% (0.7%)	1% (0.7%)	2.68% (1.87%)
	Moderate	2.7% (1.6%)	0.6% (0.4%)	0.6% (0.4%)	2.54% (1.48%)
	Strict	0.1% (0.1%)	0.1% (0.1%)	0.1% (0.1%)	0.12% (0.1%)
Arizona	Optimistic	9.6% (5.4%)	4.8% (2.7%)	4.8% (2.7%)	4.99% (2.79%)
	Moderate	9.6% (5.4%)	3.5% (1.8%)	3.5% (1.8%)	4.99% (2.79%)
	Strict	0% (0%)	0.4% (0.2%)	0.4% (0.2%)	0% (0%)
Texas	Optimistic	7.8% (5.5%)	1.1% (0.6%)	1.1% (0.6%)	4.83% (3.4%)
	Moderate	6.8% (4.7%)	0.2% (0.1%)	0.2% (0.1%)	4.24% (2.92%)
	Strict	2.5% (1.6%)	0% (0%)	0% (0%)	1.53% (1.01%)

*2010 State gasoline consumption for California, Arizona, and Texas was 56.6 Gl, 8.7 Gl, and 51.2 Gl, respectively [30].
†2010 State electricity retail sales for California, Arizona, and Texas was 258.5 TWh, 72.8 TWh, and 358.5 TWh, respectively [31].

resulting electricity exports could contribute to current light duty fleet transportation fuels (gasoline) and electricity consumption in each of the three states. For example, in the optimistic scenario, the amount of *A. tequilana* processed in the 50 km transportation buffer would provide 2.68% of California's 2010 state electricity consumption, and 2.8% of its gasoline consumption.

A. deserti has the highest state-level impact in Arizona, where it has the potential to produce as much as 4.8% of the state's gasoline consumption, and 2.5% of its electricity consumption. *A. tequilana* may also significantly contribute to Arizona's gasoline and electricity consumption – potentially contributing 9.6% and 4.9%, respectively, at the highest levels. *A. tequilana* may also significantly contribute to Texas' gasoline and energy consumption – potentially contributing 7.8% and 4.8%, respectively.

Other feedstocks

Comparing these results to the mapped potential for other feedstocks illustrates the estimated potential for *Agave* to be a complementary bioenergy feedstock because it is suitable in areas where other conventional feedstocks are not. The results from this analysis were compared to county-level estimates of future production of annual energy crops and perennial grasses from the US Billion-Ton Update (Perlack & Stokes, 2011). Areas of suitable land area for *Agave* occurring within counties with estimated future annual energy crop production greater than zero showed the most overlap in the southern tip of Texas. Of the two species studied here, *A. tequilana* showed the most overlap with other potential energy crop production, however, even in the optimistic scenario where the most land area was mapped as suitable for *Agave*, the estimated number of hectares to be planted for other annual energy crops (like switchgrass and *Miscanthus*) is only 0.8 Mha in 2020 and only 0.12 Mha in 2030 (assuming a $80 target price). When looking at modeled switchgrass yields by published Wullschleger *et al.* (Jager *et al*., 2010; Wullschleger *et al*., 2010) in the overlapping areas of Texas (in the 2030/$80 model), the average modeled switchgrass yield in the areas also mapped as suitable for the *A. tequilana* was 8.7 Mg ha^{-1} yr^{-1} (*A. tequilana* optimistic scenario) [1] – a yield well below what is documented for *A. tequilana* (24 Mg ha^{-1} yr^{-1}). In other words, even where *Agave* and switchgrass production could potentially overlap at a macro scale, for example in southwestern Texas, future switchgrass production would only use a small part of that land, and it would be a relatively low yielding crop. Therefore, it may be concluded that *Agave* will not be a major competitor to other energy crops, but rather a complementary renewable energy species that can be productive in regions where others cannot.

Discussion

This article is the first to explore the quantitative potential for agave production as a bioenergy feedstock in the United States. Based on a spatially explicit site suitability model, the results presented here suggest that there is potential for *Agave* to be grown as an energy feedstock in the southwestern region of the United States – particularly in Arizona, California, and Texas – and a significant portion of these areas are proximate to existing rail infrastructure. In the moderate scenario, 25.19 Mha of land were modeled as suitable for *A. tequilana* within the 50 km rail buffer, which equates to a total production potential of 8793 Ml of ethanol and an exported electricity potential of 26 370 GWh. Even in the strictest scenario and when limited to a 25 km rail buffer, the potential suitable land area for *A. tequilana* is still 3.7 Mha – a land area comparable to the current planted area for sorghum (3.1 Mha planted in 2013) – another drought-resistant crop drawing recent attention as a potential bioenergy feedstock in the United States (Almodares & Hadi, 2009). This amount of land under *Agave* production could still produce 1293 Ml of ethanol and an exported electricity potential of 3876 GWh. Consequently, the lowest risk strategy would be to begin production on the most suitable land areas and eventually fan out to the moderately suitable regions when the most suitable regions have been saturated.

Both *Agave* species showed the highest state-level impact in Arizona, where agave has the potential to contribute 4.8–9.6% of the states' ethanol consumption, and 2.5–4.9% of its electricity consumption, for *A. deserti* and *A. tequilana*, respectively. If additional species are incorporated to the production system, which could potentially diversify and increase the maximum suitable area for agave plantations, these numbers may be increased further. Texas may also significantly benefit from producing agave as a bioenergy feedstock – potentially seeing as much as 7.8% of its ethanol consumption and 4.8% of its electricity consumption produced by *A. tequilana* production. Considering that the total US ethanol production in 2012 was 13 300 million gallons (Renewable Fuels Association, 2013), cumulative estimates for *A. tequilana* calculate a potential production of 28.1% of total US ethanol production in the optimistic scenario within 50 km of rail infrastructure, 17.5% in the moderate scenario, and 3.8% in the strict scenario.

Feedstocks that grow where other food crops cannot have the potential to invigorate local economies, however, the actual maximum energy potential from agave plants will rely on the synergy of multiple technological factors. When converting agave plants to sugar or ethanol, there are both solid and liquid by-products, which can further add to the energy value potential of *Agave*, if downstream systems are in place to process these by-products. For example, the solid by-products can be used to generate electricity or be returned to soils as nutrients. Current generation biofuel conversion technologies (fermentation of sugars to ethanol), as well as potential next-generation technologies, (that could convert the solid material to ethanol or other hydrocarbon liquid fuels) consume heat and electricity in the plant operations.

Although agave plantations do not currently exist in these US states, the agronomic practices are well established because of the long-standing practices of commercial agave production in Mexico and elsewhere for both tequila and fiber. As a bioenergy feedstock, *Agave* spp. grown on plantations can be managed on a short-rotation forestry-type production cycle, with approximately 5 years interval between planting and harvest. In this way, growing agave as a bioenergy feedstock is more akin to short-rotation forestry production (e.g., poplar production) rather than perennial grass species, like switchgrass and *Miscanthus*. However, an additional consideration is that current agave plantations typically leave agave leaves on the soil to maintain soil nutrients. The absence of returning solid from biorefineries to soils might result in the plantation's use of organic fertilizers which would reduce the overall life cycle and sustainability of agave-based biofuels and or electricity (Davis *et al*., 2011). Thus, utilizing agave solid by-products as a heat and or power feedstock must be weighed against the costs and benefits of returning the plant material to the plantation soils.

Looking forward to a future with a changing climate, CAM species like *Agave*, which are adapted to extreme high temperatures and drought conditions, are more likely to withstand variable temperatures and rainfall predicted in future climate over the next century. In fact, *Agave* and plantation yields are likely to benefit from increased temperatures and CO_2 levels that accompany climate change because net CO_2 uptake in *Agave* increases as CO_2 levels increase (Drennan & Nobel, 2001; Garcia-Moya *et al*., 2011). In addition, increasing temperatures, particularly increasing minimum nighttime temperatures and decreasing freezing days (both of which are currently limiting factors for *Agave*), may expand the land potential for the species.

It should also be noted that potential agave production in the United States is not limited to the two species evaluated in this study; in fact, 25 *Agave* species are native to the southwestern United States (Garcia-Moya *et al*., 2011). Of the two species reviewed here, high-yielding *A. tequila*na is more likely to be actually used for bioenergy purposes. *A. deserti* is used here as more of a comparator species that can be used to evaluate the extremes for the genus *Agave*, but is not a likely candidate for immediate deployment in biofuel applications. Moreover, some *Agave* species not native to the United States, such as *A. salmiana* (42 Mg ha^{-1} yr^{-1}) and *A. mapsiaga* (38 Mg ha^{-1} yr^{-1}), under ideal cultivated conditions are known to produce even higher yields than the species studied here (Escamilla-Treviño, 2012). However, empirical data for these species that is necessary to drive the model used in this study are not currently available. For this reason, there is a need for more research involving rigorous replicated field trials to better understand tolerance ranges of additional *Agave* species, and how varied climates affect agave production and yield patterns.

As additional *Agave* species are targeted for future research and as more empirical data become available, this working model can easily be modified to map their potential in the landscape. The model used here incorporates fuzzy logic, which provides a more differentiated result by showing degrees of membership to the desired criteria. The sensitivity analysis revealed that the suitability for the *Agave* species studied here is most restricted by climatic variables – as opposed to physical soil factors – which prove to be a major factor in determining mapped suitable area. Particularly, minimum temperature in winter months is the most influential criterion restricting land area suitable for agave cultivation in these regions. Therefore, *Agave* with a relative tolerance to cold temperatures, while also producing high yields, will have a distinct advantage as a bioenergy feedstock in the United States, and selective breeding or engineering of *Agave* with these traits should be a priority for the development of bioenergy-optimized agave cultivars.

Meeting the demand for safe, reliable energy will take a diversity of renewable energy sources. Biofuels have been identified as a critical component to achieving a more sustainable future by supplying a low-carbon option for difficult to decarbonize portions of the transportation sector (Williams *et al*., 2012; Wei *et al*., 2013). In addition to electricity generated from a low-carbon electricity generation sector, and in combination with economy-wide energy efficiency improvements, bioenergy will help displace current fossil fuel combustion in building and transportation sectors. Although the arid and semiarid southwestern US regions are endowed with large solar electricity potential, they are limited in their ability to produce conventional low-carbon bioenergy feedstocks and have few options available for supplying residual liquid fuel demand other than importing biofuels from other regions. This not only adds costs to bioenergy use but also reduces the carbon benefits (through long-distance transportation), and denies these regions the economic prosperity associated with producing their own fuels. This article illustrates that given the right physical conditions, agave plants have the potential to complement conventional bioenergy crops given its ability to grow on land not currently utilized by agriculture or other potential bioenergy crops. Policymakers seeking to advance low-carbon intensive energy supplies and regional job development in the dry southwestern US should consider agave-derived bioenergy development.

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