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Drought-tolerant Biofuel Crops could be a Critical Hedge for Biorefineries

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INTRODUCTION

Numerous researchers and policymakers have raised concerns over the adverse effects that growing bioenergy crops on prime agricultural land has on food prices, carbon balances, water demand and environmental health [1-5]. Biofuel policies such as the California Low Carbon Fuel Standard (LCFS) and the second US Renewable Fuel Standard (RFS2) already regulate biofuels for carbon emissions that occur due to indirect land use change [6, 7]. Biofuel producers can address these concerns and sidestep steep penalties for indirect land use change if they grow biofuel crops on land that has little or no economic value.

The focus of most biofuel research over the last decade has been the development of biofuels from cellulosic feedstocks [8]. It has been argued that deriving biofuels from non-food biomass, like switchgrass, and growing the crop on low value land would minimize competition with food production [9, 10] [11, 12]. Moreover, using non-irrigated rain-fed feedstocks can substantially reduce the lifecycle footprint of cellulosic biofuels [13]. This has motivated scientists to study if biofuel crops can be genetically engineered to thrive on low-value, marginal lands [14]. One example is the development of switchgrass genomics designed to enhance productivity [15, 16].

For a biofuel business, investing in the development of a product in expectation of a specific policy regime (i.e. the regulation of land use in fuel policy) is fraught with risk [17]. While we believe that all fuel policies worldwide should reward biofuel crops grown on land that has little or no potential for growing food crops, there is good reason to believe that such globally coordinated policy on the subject of land use is unlikely [5]. Hence, in this article, we assess the economic benefits of drought-tolerant switchgrass that may accrue to biofuel businesses independent of any incentives for the use of marginal land.

The frequency of extreme weather and drought has increased in the U.S. over the last decade [18-20]. While some researchers estimate that droughts are decreasing in severity and duration [21], most climate scientists report that advancing climate change is expected to worsen droughts throughout the U.S., especially in the Midwest, which is the nation's largest producer of food crops [22-24]. Scientists are increasingly convinced that climate change is leading to warmer extremes including severity of precipitation extremes [25]. In the more likely scenario of worsening drought, we find that drought-tolerance of the cellulosic crop is critical for the biofuel industry to remain competitive, irrespective of whether the crop is grown on marginal or prime agricultural land. In other words, we find that over the lifetime of a typical biorefinery, there could be one or more years when a crop is likely to be severely diminished due to drought conditions, thereby driving cellulosic ethanol prices substantially higher than would otherwise be the case.

METHODS

Forecasts of U.S. switchgrass production potential and rain water availability indicate that Kansas is an ideal state for estimating the effect of drought conditions on ethanol production and prices. U.S. Midwestern states east of Kansas have historically had greater and more consistent precipitation rates than those west and have thus faced fewer drought years [26]. Performing the same analysis using historic data for these states would not likely reveal interesting results with respect to drought conditions. However, recent climate model results indicate that climate change could produce a drying trend throughout the U.S. Midwest over the next century [22-24]. If a Midwest drying trend does prevail then states east of Kansas could have precipitation patterns similar to Kansas's historic pattern, and Kansas could become even drier. Therefore we focus on Kansas's historic data to show that drought conditions pose a significant risk to future biofuel production, a risk that will likely be present throughout the U.S. Midwest in the coming century if climate change predictions come true.

We couple a high-resolution spatial analysis of rain water availability with a supply chain cellulosic ethanol production cost model. The focus of the analysis is to highlight the risks biorefineries may face in drought conditions rather than provide an in-depth analysis of biorefinery supply chain economics. Thus our cellulosic ethanol production cost model is predicated on previously published reports for economies of scale and technology learning over time scaled to current estimates for cellulosic conversion efficiencies and costs [27, 28]. See supporting online materials for a detailed description. Although a biochemical cellulosic ethanol production process is modeled, the risks associated with drought conditions would apply to any biofuels conversion technologies that are reliant on switchgrass.

HIGH RESOLUTION SPATIAL ANALYSIS OF WATER AVAILIBILITY

Figure 1 shows that Kansas has a wide range of average annual precipitation levels, from as low as 380 mm (15 inches) per year in the southwest to over 1,100 mm (42 inches) per year in the southeast. PRISM data was used to generate Figure 1 [26]. PRISM data is developed through a joint partnership with the U.S. Department of Agriculture's Nation Resource Conservation Services through its National Water and Climate Center (NWCC) and the PRISM group at Oregon State University. PRISM data consists of monthly, yearly, and event-based parameters including temperature and precipitation, among others.

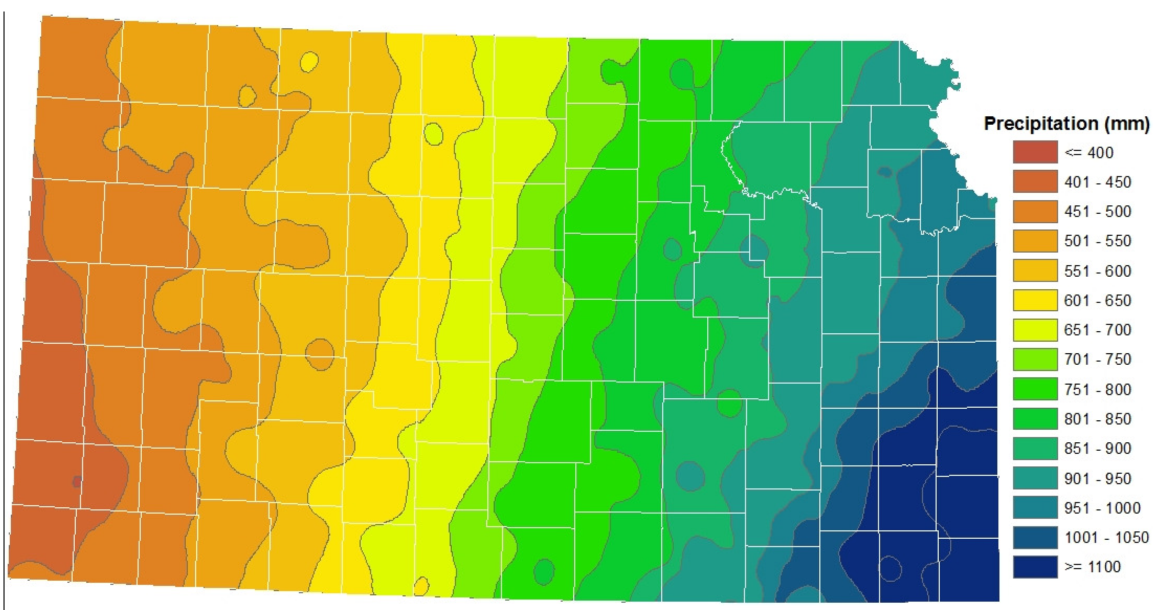

Figure 1. Annual Average Precipitation for Kansas from 1971 to 2000. Source: NRCS & OSU PRISM [26]

Although several established methods exist for measuring droughts, a new drought index was needed for the present analysis, because existing indices either deal with time periods too long for switchgrass or focus only on assisting with irrigation management. The drought indices most widely used are the Palmer Drought Index [29] and the Koppen climate classifications [30]. However, we exclude both since they are most effective in quantifying the severity of long-term droughts on the scale of months or years, while switchgrass appears to lose harvestable biomass during drought conditions on the scale of weeks [31]. A soil dryness index has been developed and applied in Australia that measures daily soil moisture over a season to determine fire management strategies, but the methodology does not focus on duration of dryness but instead observes seasonal effects on soil moisture [32]. A Crop Water Stress Indicator is capable of shorter time-scales, but estimates how crops react to water stresses by measuring the amount of transpiration based on plant leaf temperatures [33]. This indicator is used 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. The Water Deficit Index is another technique that was developed to estimate crop water deficits based on inferred sensing and measurements of surface air temperatures [34]. A similar technique also based on spectral imaging was applied to grasslands in the Midwest (Kansas and Oklahoma) and found to accurately measure drought conditions [35]. However, these are focused on helping identify when a drought is occurring in order to inform crop management and the use of irrigation. These methods too, are meant for irrigation intervention and do not enable us to quantify the severity of past droughts.

The precise response of switchgrass to water scarcity at its roots has been understudied, primarily because it has not been an important crop in the U.S. However, we do know that a dry spell of seven weeks significantly diminishes harvestable yields [31] and infer that plant yield drops precipitously as each dry spell lengthens. In other words, the effect of a series of four 2-day dry spells is less than the effect of a single 8-day dry spell on switchgrass yield. Based on this understanding, we develop a drought index that should be well correlated with the effect of dry spells on switchgrass growth and hence can sustain the main conclusions of this article.

We developed our dryness index using high resolution weather and soil data to provide a measure of dry spell severity for switchgrass. We integrated daily weather data from 1996 to 2005, obtained from NOAA weather stations and kindly provided by Schlenker [36] including the maximum and minimum temperature, and precipitation on a 4 km grid to estimate inches of water stored in the soil on a daily basis. Rainfall adds to the water level, capped by local field capacity, and evapotranspiration depletes the stored water. We used U.S. Geological Survey soil data on field capacity and water table depth to calculate the local soil storage capacity [37]. Evapotranspiration is calculated by the Hargreaves method, which uses only the maximum and minimum temperature, and extra-atmospheric solar radiation, which we calculated based on the latitude of each grid cell [38, 39]. We assumed an evapotranspiration crop coefficient of 1, which is an average for corn and switchgrass [40, 41].

Based on the soil moisture we look for extended periods of drought or "dry spells," which are periods when the soil moisture is below the Maximum Allowable Depletion for a given crop and root depth. Below the Maximum Allowable Depletion a given crop's roots have difficulty extract moisture from the soil which causes water deficit stress. We assume a Maximum Allowable Depletion of 50% for switchgrass [41]. Days in which soil moisture falls below this threshold are considered dry days. Dry spells are multi-day periods during which the soil moisture remains below this level. The dryness index for each 4 sq-km grid cell is the sum of the squares of the 4 longest dry spells during the growing season (April - September) measured in days. Our chosen index metric should be further refined with field research but is based on intuition; longer spells are given a higher weight (squared) and multiple dry spells (expected to weaken the crop) are included.

For the full detailed explanation of the dryness index approach, please refer to the supporting online material

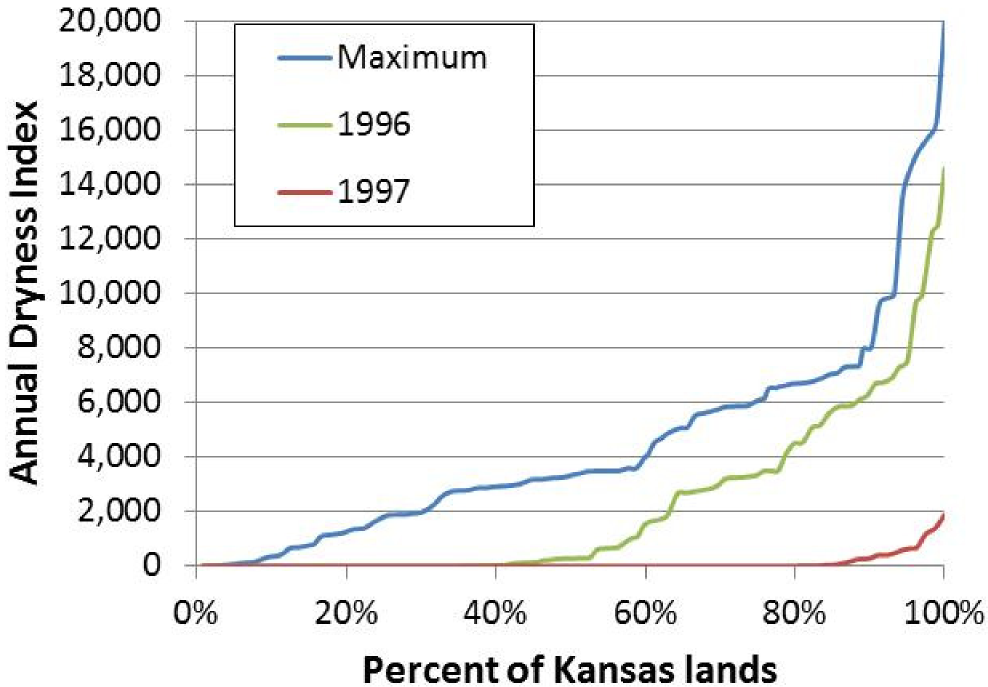

Figure 2. Percentage of Kansas Lands affected by Dry Spells

Figure 2 shows the percent of Kansas's lands that experience annual dry spell conditions over the calculated range of indices. Two single years (1996, a dry year, and 1997, a wet year) is presented along with the annual maximum over the 10 years analyzed. The dryness index goes up to 20,000 representing between roughly 4, 70 day long-long dry spells, or a single 140 day-long dry spell. Figure 2 shows that a wide range of drought conditions can happen between two consecutive years. During 1996, a particularly dry year in the dataset, roughly 40% of Kansas experienced dryness indices greater than 2000. Looking at the maximum dryness index over the 10 year period, roughly 70% of Kansas experienced at least one year with a dryness index above 2,000.

Figure 3 shows the maximum annual dryness index in each county in Kansas over the 10 year time period analyzed. We find that moderate to severe dry spells occur in many parts of the state, including in areas that receive greater annual rainfall on average. For example, the northeast corner of Kansas shows relatively moderate average annual rainfall levels in Figure 1, but experienced similar maximum dry spell conditions as the western half of the state. We see the reverse effect in one county in the northwestern quadrant of the state. Thomas County (labeled in Figure 3) has one of the lowest maximum drought index numbers in the state despite being located in the dryer half of the state. We find that a correlation coefficient of (-)25% between the maximum annual dryness index and the average annual rainfall for each county is not very strong. In fact, the correlation coefficient between annual dryness index and annual rainfall for each county is weak in all years (ranges between (-)11% and (-)41%) indicating that dry periods are not predicted by annual rainfall.

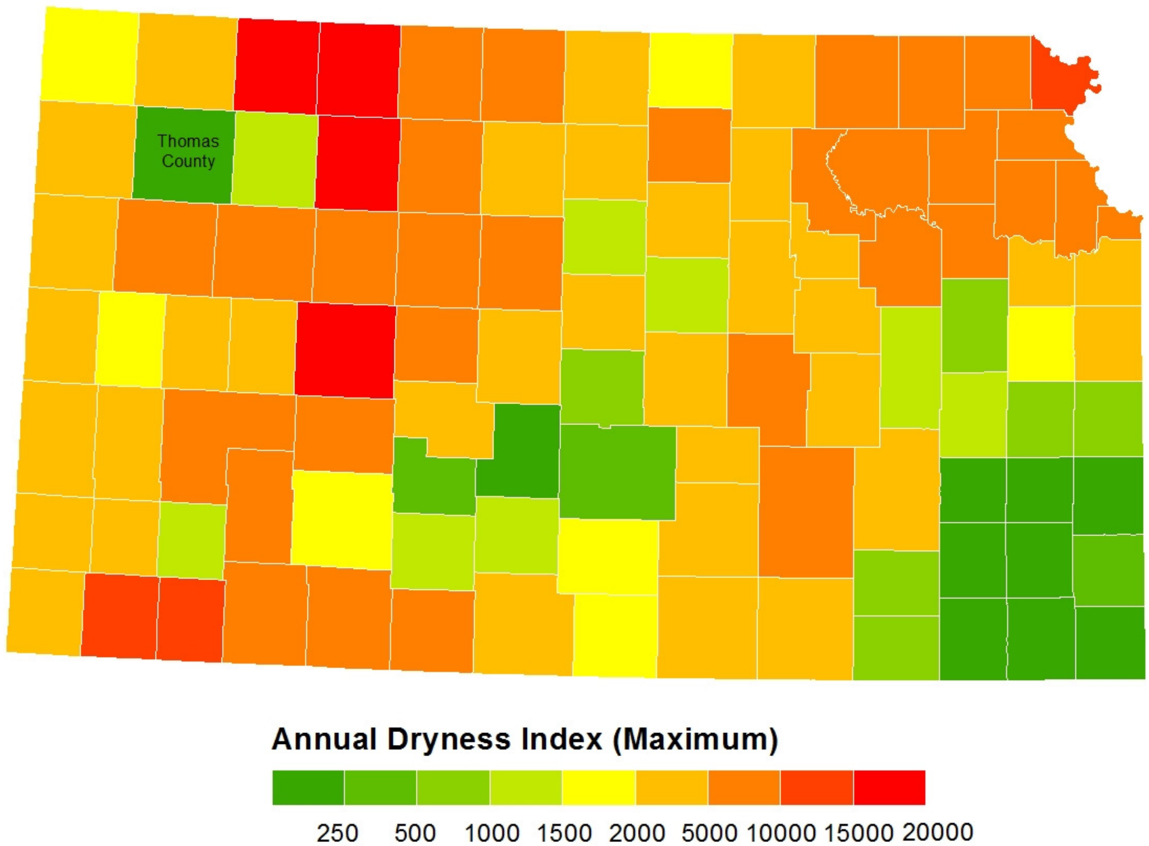

Figure 3. Maximum Annual Dryness Index by County from 1996 to 2005

SWITCHGRASS PRODUCTION: YIELDS AND THE EFFECT OF DROUGHT

There are very few estimates of the determinants of switchgrass yield. We use a statistical estimate for switchgrass yields based on 1,190 observations from 39 field trials conducted across the United States [42]. According to the study by Wullschleger et. al. [42], the main determinants of switchgrass yield are average annual growing season precipitation, nitrogen fertilization, latitude, and switchgrass variety. The authors do not characterize the effect of prolonged dryness on yield..

Some literature suggests that switchgrass is relatively more drought tolerant than other potential bioenergy crops such as miscanthus [43, 44]. Other researchers have forecasted increased switchgrass yields under climate change related warming and atmospheric CO2 concentrations but make no mention of drought occurrences [46]. Researchers in Texas reported the resilience of switchgrass due to its high capacity to respond to favorable growing conditions following an extreme drought (less than 15 cm of growing season precipitation) but noted that low yields were experienced during the drought [47]. Switchgrass production across the entire United States has been estimated using the EPIC (Environmental Policy Integrated Climate) process which estimates daily growth based on switchgrass test plot results and weather conditions [48]. Although the EPIC report does not discuss the effects of droughts on switchgrass production, it does mention that low precipitation is a limiting factor across the western half of the United States.

Several researchers have found that switchgrass is much more sensitive to soil moisture deprivation than other warm-season grasses [45]. A summary report of early bioenergy feedstock field test noted that successful switchgrass plantation establishment was difficult due to droughts [49]. An earlier study observed that in dryer climates, a single harvest per season was better than two harvest per season due to limited precipitation [50]. Sanderson et. al. [50] reported that a severe drought in the first half of 1996 reduced yields dramatically (roughly halved) at one test site. Barney et. al. [31] studied switchgrass responses to extreme moisture conditions including drought with the objective of evaluating switchgrass fitness to extreme conditions [31]. They focused on germination, establishment, performance and reproductive potential of two common varieties (upland and lowland) of switchgrass subjected to controlled, flooded, drought (5% soil moisture), and extreme drought (3% soil moisture) conditions. They do not report the length of the extreme drought experiment but did report that the drought (5% soil moisture) condition was sustained over seven weeks and reduced the above ground biomass (harvestable biomass) by close to 80%. The extreme drought further reduced aboveground biomass to approximately 85% below the control case. They concluded that in both the drought and extreme drought cases the root system lives but the reproduction rates are halved in addition to the dramatic reduction in above ground biomass. The researchers did not, however, report yield response to dryness as a function of time and therefore it is not possible to draw conclusions about any optimal drought tolerance target from this work. Although, we assume that drought conditions begin when the soil moisture at root level drops below 50%, versus 5%, a seven week drought period would correspond to a drought index of 2000 in our calculation.

For our purposes, it is not necessary to find an exact relationship of yield to the dryness index. Instead, we seek to highlight the relationship between drought conditions, resulting feedstock losses and diminished biorefinery output and revenue. Hence, in our study we use a simple step response that models negligible switchgrass production if the dryness index exceeds a threshold. The step response models the annual output of a biorefinery assuming that yield losses will be annual losses. A step response also means that we do not attempt to determine incremental switchgrass losses with increasing dry spells. The advantage of using a step response is that we can vary the threshold and estimate the resulting drop in ethanol production and resulting increase in ethanol plant gate costs as the threshold is further reduced. This allows for a simple relationship to be shown between ranges of drought-tolerance and biorefinery risk.

SUPPLY CHAIN ECONOMICS OF SWITCHGRASS ETHANOL

Current biofuel policies in the U.S. include climate goals and, therefore, explicitly prefer biofuels with the lower lifecycle carbon content [6, 7]. Future biofuel policies are likely to be designed similarly because biofuels are widely seen to play a big role in mitigating carbon emissions from the transport sector. Sourcing rain-fed feedstocks and minimizing feedstock transportation distances are two measures that can substantially reduce the lifecycle carbon footprint of biofuels. Hence, in our economic analysis, we model biorefineries that source only non-irrigated switchgrass supplied from local lands.

It is not our intention to forecast where cellulosic ethanol plants will be or should be built but instead to highlight the effect that dry spells could have on ethanol plant outputs and prices. Therefore, we chose to divide Kansas into quadrants of roughly the same area and assume that a 757 million liter per year (200 million gallon) ethanol plant is built in the center of each quadrant. We assume that each quadrant's biorefinery procures enough switchgrass feedstock to supply the plant at full capacity annually based on average rainfall. Furthermore, we assume that switchgrass production is spread equally across each quadrant and that each biorefinery contracts only with farmers in its quadrant for switchgrass supply and no switchgrass is stored between years. Given our calculated average yields of switchgrass, we find that roughly 1.75% of Kansas's land will be in switchgrass production under such a scenario. We label the quadrants as North-East (NE), North-West (NW), South-West (SW), and South-East (SE)

We calculate ethanol production cost assuming that each biorefinery always attempts to recover its cost of capital for that year. Any attempt by the biorefinery to postpone capital cost recovery will simply trade lower ethanol costs this year for higher costs in later years. Our supply chain economic model includes technological learning and economies of scale in addition to the basic costs of feedstock production, transport and conversion [27, 28]. Assuming mature cellulosic ethanol process design and costs we estimate the ethanol plant-gate cost to be approximately $0.82 per liter ($3.10 per gallon) gasoline equivalent in the average precipitation year, in 2009 dollars.

For the full detailed explanation of the supply-chain economic model, please refer to the supporting online material.

RESULTS

We generate a relationship between drought tolerance thresholds and the annual ethanol production cost for each biorefinery for each year between 1996 and 2005. We assume that the drought tolerance threshold is the lowest dryness index at which harvestable switchgrass is produced. As discussed before, we assume that if the annual dryness index of any county is higher than the threshold value, the county will not produce any switchgrass that year. We report plant-gate ethanol costs for each plant for dryness thresholds that vary from 0 to 6000.

Figure 4 shows the relationship between the drought tolerance threshold and the cost of ethanol produced for each biorefinery for two select years 1996 and 2000, both expressed in 2009 dollars. Unsurprisingly, the biorefineries located in the drier Western half of Kansas suffer from a substantial feedstock deficit for any drought tolerance threshold levels below 3000 in the year 1996 data. But surprisingly, the wetter eastern half of the state also suffers from feedstock deficits in the year 2000 data, a year when the drier western half of the state is less affected.

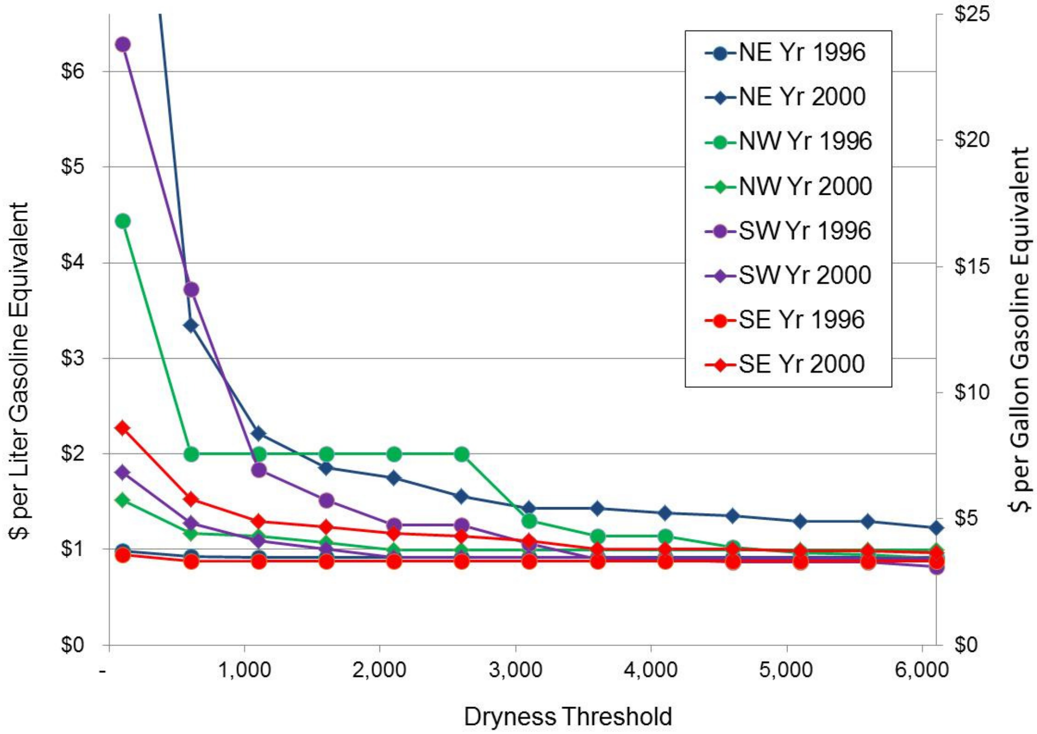

Figure 4. Plant-gate Ethanol Cost as a function of Drought Threshold for 1996 and 2000 (in 2009$)

Since we recognize that our dryness index may not be perfectly correlated with switchgrass response to drought as we discuss above, we present results (in Figure 5) that show plant-gate prices for the very conservative dryness index of 2000, the threshold at which Barney et al have shown that switchgrass is severely diminished. Even in this very conservative case, each of the quadrants experiences at least one year with higher costs including the wetter South-Eastern quadrant over the time period.

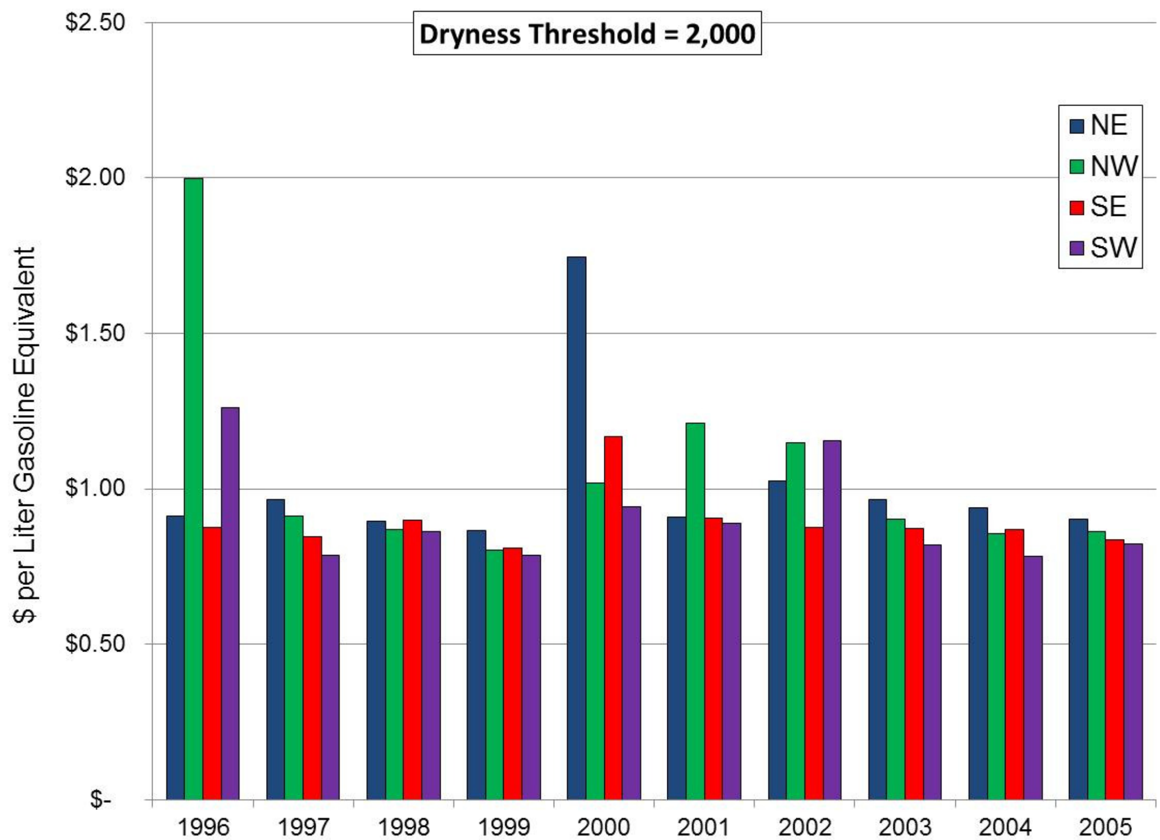

Figure 5. Plant-gate Ethanol Cost as a function for each Biorefinery from 1996 to 2005 for a Drought Threshold of 2000

If we assume that switchgrass yield is severely reduced at a drought threshold of 2000, as suggested by data in Barney et. al. [31], ethanol plant gate costs in each biorefinery would have exceeded $1.17 per liter ($4.42 per gallon) gasoline equivalent in at least one year of the analysis decade. These high costs would be worsened if significant switchgrass losses occur at lower dryness indices. During the worst years for Western quadrants (1996) we estimate that output would have fallen to 135 million liters (36 million gallons) in the north and 269 million liters (71 million gallons) of ethanol in the south. During the worst year for the Eastern quadrants (2000) we estimate that output would have fallen to 198 million liter (52 million gallons) in the north and 383 million liters (101 million gallons) of ethanol in the south.

We performed a sensitivity analysis of several key variables influencing plant gate costs. A range of values represented in literature are used to define the upper and lower bounds that each variable could have on plant gate prices (see SOM for details). The sensitivity results are presented in Figure 6.

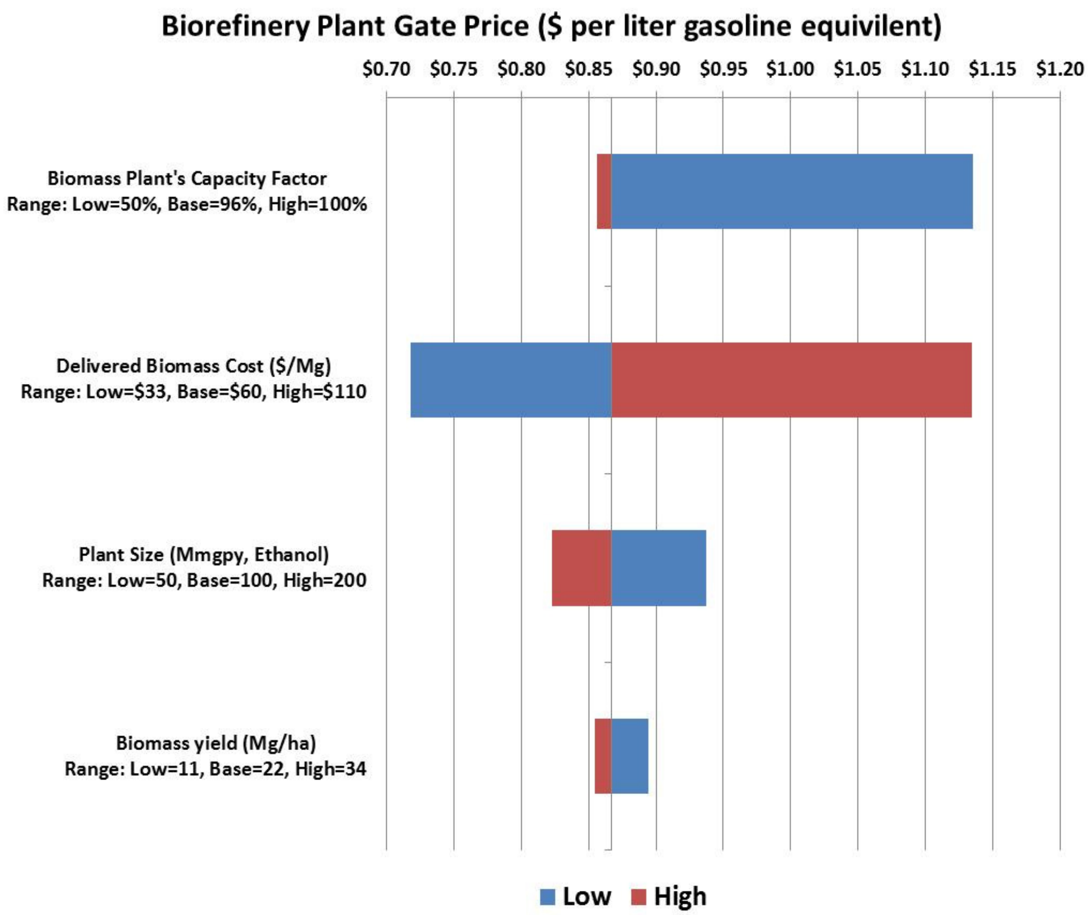

Figure 6. Sensitivity Analyses of Ethanol Plant-gate Costs

The sensitivity analysis shows that the variable that most influences plant gate prices is the cost of feedstock. Seeking to be as cost competitive as possible biorefineries will probably avoid contracting for more feedstock supplies than necessary as a hedge against potential drought occurrences. This would raise the overall plant gate prices for every year to pay for additional contracted feedstocks. Over contracting would also over produce feedstocks that would necessitate additional storage and could result in significant feedstock losses. The capacity factor, which is strongly dependent on feedstock availability, is another major determinant of plant-gate costs. Drought-tolerant switchgrass will obviously be one of the ways in which biorefineries can mitigate the risk of capital under-utilization. It is important to note that our choice to model a 757 million liter per year biorefinery does not significantly lower the cost relative to a mid-size biorefinery and hence is not an assumption that strongly affects our main conclusion. The low effect of biomass yields on ethanol price is a short-run effect since we assume that biorefineries have fixed-price contracts with farmers for feedstock. Hence farmers are unable to pass on higher costs due to low yields in any given year but they will surely attempt to renegotiate the contract prices if low yields persist (see supporting online material for a more detailed explanation of the supply chain economics model).

DISCUSSION

The ability to use marginal land to grow biofuel crops is the reason most often cited to develop hardier biofuel crop varieties like drought-tolerant switchgrass. This is driven by expectation of policy that will legislate against the indirect effects of land use for biofuels. Our study shows that drought-tolerance is likely to be a biofuel crop feature that will have substantial economic value irrespective of policy rewards for the use of marginal lands.

Our study is also valuable to policy makers concerned with promoting the use of biofuels. Recognizing that biorefinery outputs could face drought-caused interruptions, policies with fixed annual volumetric mandates may not be realistic in the absence of drought-tolerant biofuel crops. Even if individual biorefineries are insulated from the financial risks identified by this analysis they still may not produce a constant fuel output every year. If the volumetric targets of the RFS2 are met with significant regional dependency it will be important to protect those regions or the crops grown in those regions from drought risk.

The private economic value of drought-tolerant biofuel crops further increases if climate-induced drying trends across prime U.S. farmland in the Midwest become reality. Early commercial second-generation biofuel plants are likely to source feedstock from prime agricultural land in order to compete with gasoline but even those would need to be insured against feedstock availability risk. While other options are available to mitigate this risk, like drought insurance or federal crop insurance, all of these are likely to have higher social or private costs than drought-tolerant crops.

Our study is valuable to biorefineries and switchgrass geneticists, as a complement to the work of Barney et. al. [31], by highlighting this relationship and encouraging additional research in this area to better understand the performance of feedstocks under drought conditions. For example, knowing the harvestable losses as a function of drought duration, and knowing when in the growing season droughts occur would help this research better anticipate the effects of droughts in biorefinery output and prices. It is very difficult to predict the future, but it is clear that drought effects should be mitigated so future biorefineries will be successful at delivering low-cost, low-carbon biofuels that do not require food sacrifices.

ASSOCIATED CONTENT

Supporting Information.

Mathematical equations detailing our dryness index calculation

A discussion of the techno-economic cellulosic ethanol modeling approach

This material is available free of charge via the Internet at http://pubs.acs.org.

For instructions on what should be included in the Supporting Information, as well as how to prepare this material for publication, refer to the journal's Instructions for Authors.

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. ‡These authors contributed equally. (match statement to author names with a symbol)

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