Feedstock Loss from Drought is a Major Economic Risk for Biofuel Producers

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ABSTRACT

High cost of technology is seen as the primary barrier to full commercialization of cellulosic biofuels. There is broad expectation that once conversion technology breakthroughs occur, policy support is only needed to accelerate cost reductions through “learning by doing” effects. In this study, we show that droughts pose a significant economic risk to biofuel producers and consumers regardless of the rate at which technology costs fall. We model a future switchgrass derived cellulosic biorefinery industry in Kansas based on spatially resolute historic (1996 to 2005) weather data, representing a rainfall regime that could reflect drought events predicted to

occur throughout the U.S. Midwest by climatologists (Karl, et. al. (2009) U.S. Global Change Research Program USA). We find that droughts reduced modeled biorefinery capacity factors, on average, by 47%, raising biofuel production costs by 35% between a modeled dry and wet year. Interestingly, we find that two logical strategies to plan for drought; (1) building large biorefineries to source feedstock from a larger area and, (2) Storing switchgrass in good production years for use in drought years; are not very effective in reducing drought risks. Our findings should be of particular concern to low carbon fuel policies like California's Low Carbon Fuel Standard and the U.S. Second Renewable Fuel Standards (RFS2) whose costs of compliance may be much higher than expected.

KEYWORDS

Switchgrass
Droughts
Biorefinery
Techno-economics
Supply chain
Climate change

INTRODUCTION

Research has shown that most vehicle technology and clean fuel options to reduce greenhouse gas (GHG) emissions from transportation come at a high carbon abatement cost when compared to other energy sectors like power [1-4]. However, estimates show that second generation biofuels have the potential to displace a substantial share of petroleum use in transport [5-8]. There is also broad agreement that the primary barrier to full commercialization of cellulosic biofuels is the high technology cost [9-11] and cost reductions after commercialization could be rapid [12]. Finally, although the carbon mitigation potential of biofuels have been questioned vigorously [13-16], both biofuel critics and proponents agree that cellulosic biofuels offer significant carbon reductions over petroleum especially if the feedstock is grown on lands that have low opportunity costs and limited potential for cascading indirect land use change effects [17]. Lifecycle environmental impacts are further reduced for non-irrigated feedstocks [18].

Each of these widely held views have played some role in the design and enactment of low carbon fuel policies like the US Second Renewable Fuel Standard (RFS2) [19], the California Low Carbon Fuel Standard (LCFS) and the European Union's Renewable Energy Directives (EU RED) for transportation [20]. All of these policies set their targets under the implicit assumption that cost-effective biofuels would play a key role in meeting them. .. While each of these transportation fuel policies are designed for some level of planned or forced flexibility (e.g., EPA has waived mandated volumes due to a lack of capacity) each is expecting biofuels to fulfill the majority of the targets because vehicles that use other alternative fuels like electricity or hydrogen are not expected to be a significant part of the fleet by 2020 [20, 21]. Hence, these Governments may have enacted fuel policies with less ambitious targets had expert opinion on the potential and projected production cost trends for cellulosic biofuels not been so optimistic.

In this paper, we study the effects of drought on the production costs of cellulosic biofuels and find that it poses a substantial risk to farmers and biofuel producers regardless of assumptions on biofuel technology development. The effects of drought are ignored in studies of biofuel supply chain economics [9, 22], although climate studies predict that extreme weather events, including drought events, will become more frequent in the U.S. Midwest [23-28], where most of the nation's biofuel crops are likely to be grown [29, 30]. Our research suggests that the ethanol price spikes caused by the 2012 drought [31] could recur in future droughts when demand for low carbon biofuels could be substantially higher and necessary to achieve deep greenhouse gas emission reduction targets [19, 32].

Most US biofuel experts expect that switchgrass and miscanthus will be the two major purpose grown crops for a sustainable US biofuel industry, with switchgrass being better suited to the Midwest [29]. Switchgrass is chosen as the feedstock in this study because its response to drought conditions is better understood than miscanthus, although both are understudied. Our results are not likely to change qualitatively for Miscanthus, the other promising biofuel crop for the U.S. Midwest, [30] because it is less drought tolerant than switchgrass [33]. Using historic weather data from 1996 to 2005 we develop a methodology for estimating dry periods that will affect switchgrass yields. We then derive annual biofuel cost curves for rain fed switchgrass derived cellulosic biorefineries located in Kansas (see the Methods section for an explanation of why we chose Kansas). We model three scenarios, one with no drought planning and two more where biorefineries take measures to mitigate drought risks:

1. In Scenario 1, we model switchgrass production on existing Conservation Reserve Program (CRP) lands¹, which we use as a proxy for marginal lands, and a biorefinery in each county supplied exclusively from switchgrass production within that county. Biorefineries are sized under the assumption that there will be no drought induced feedstock loss and the production cost of ethanol is estimated using the biorefinery economic model described in the Supplementary Material.
2. In Scenario 2, an “aggregated” scenario, roughly six to eight counties are aggregated together to supply larger biorefineries, with the goal of spreading drought risk across a larger regions. As in Scenario 1, CRP lands are used and biorefinery are sized using the same methodology as in Scenario 1. A maximum capacity of 757 million liters per year (200 million gallons) is modeled with some regions having multiple biorefineries at this maximum size.
3. In Scenario 3, a “storage” scenario, biorefineries are sited and sized as in Scenario 1 but plan for drought by a) under-sizing biorefinery capacity by 10%, b) contracting for the same switchgrass supply as in the previous scenarios, and c) having available storage for the additional annual switchgrass supply. We apply a storage capital cost adder (described in the biorefinery supply chain economics below).

We present results on a “relative costs” basis with 100% being the lowest production cost result across the three scenarios which is \$0.74/gle (\$2.82/gge)² for mature cellulosic ethanol technology. If we assume current cellulosic ethanol technology the costs are \$1.28/gle

¹ CRP lands are lands voluntarily taken out of agricultural production by farmers and are commonly used as a proxy for marginal lands.

² gle is gasoline liter equivalent & gge is “gasoline gallon equivalent” which is the energy equivalent of a liter (or gallon) of gasoline.

(\$4.85/gge) which is consistent with current cellulosic ethanol costs estimates [9, 11]. We chose to present results on a relative basis to draw attention to the drought effects rather than speculations of future cellulosic ethanol process maturity and costs (see supplementary material for cellulosic ethanol processes and cost estimation methodology). Our costs include a farm-gate price for switchgrass, transportation cost between farms and biorefineries, and the long-term marginal cost for biorefineries (this includes capital costs, depreciation, and return on investments). In Figure 4 through Figure 6 “relative costs” are the normalized cost results from the scenarios (i.e., the estimated costs divided by the lowest production cost result across the three scenarios).

METHODS

Forecasts of U.S. switchgrass production potential and rain water availability indicate that Kansas is an ideal state for estimating the effect of future climate change driven drought conditions on ethanol production and costs. U.S. Midwestern states east of Kansas historically have had greater and more consistent precipitation rates than those further west and have thus faced fewer drought years [34]. Performing the same analysis using historic data for these states would not likely reveal future cellulosic biofuel risks from drought. However, studies indicate that climate change will produce more frequent and longer lasting extreme weather events with drought being one of these [24-28]. If these forecasts come true then states east of Kansas could have precipitation patterns similar to Kansas’s historic pattern, and Kansas could face more frequent droughts. Although climate models forecast trends at regional scales such as the U.S. Midwest, they are poor tools for forecasting precipitation at sub-county scales. Moreover, while they appear reasonable at predicting seasonal weather effects, sub-seasonal time resolutions are necessary for calculating the effects of droughts on switchgrass yields. Detailed daily historic

weather records at field scales are available for the U.S. and we focus on Kansas's historic data to show that drought conditions pose a significant risk to future biofuel production, a risk that could 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 historic weather data [35] with a supply chain cellulosic ethanol production cost model. Switchgrass yields are estimated based on references for both annual growth predictors [36] and drought responses [37] through the development of a unique dryness index that measures the duration of periods when the soil moisture is low enough to stress switchgrass. We assume "mature" cellulosic ethanol biorefineries predicated on previously published reports for economies of scale and technology learning over time which lower capital costs and improves conversion efficiencies [12]. However, recent analysis of cellulosic ethanol biorefineries indicated that capital costs are much higher than in the earlier reports [10, 11]. We assume the more recent analysis of cost and conversion efficiencies set the near-term ethanol costs but then biorefineries "mature" by following the earlier estimates for rates of learning over time [11, 12]. See supplementary material 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 or other rain fed herbaceous bioenergy crops or residues.

SWITCHGRASS PRODUCTION: YIELDS AND THE EFFECT OF DROUGHT

We use a statistical estimate for switchgrass yields based on 1,190 observations from 39 field trials conducted across the United States [36]. According to this study, 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 [33, 38]. Other researchers have forecasted increased switchgrass yields under climate change related warming and atmospheric CO₂ concentrations but make no mention of drought occurrences [39]. 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 [40]. Switchgrass production across the entire U.S. has been estimated using the EPIC (Environmental Policy Integrated Climate) process which estimates daily growth based on switchgrass test plot results and weather conditions [41]. The EPIC report does mention that low precipitation is a limiting factor across the western half of the U.S. but do not use the EPIC model because it does not include daily growth response to drought conditions. Several researchers have found that switchgrass is much more sensitive to soil moisture deprivation than other warm-season grasses [42]. A summary report of early bioenergy feedstock field test noted that successful switchgrass plantation establishment was difficult due to droughts and at precipitation ranges as low as 100 mm per year switchgrass yields were roughly half the yield at 150 mm per year [43]. An earlier study observed that in dryer climates, a single harvest per season was better than two harvests per season due to limited precipitation [44]. Sanderson et. al. [44] reported that a severe drought in the first half of 1996 reduced yields dramatically (roughly halved) at one test site. Barney et. al. [37] studied switchgrass responses to extreme moisture conditions including drought with the objective of evaluating switchgrass fitness to extreme conditions. 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 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 how switchgrass responds to shorter drought periods, or how it performs following the drought exposure.

Although a more exact relationship of yield over a range of time would provide greater resolution to our analysis we use a simple step response that models negligible switchgrass production (80% loss) if the dry periods exceeds the seven week drought from Barney et al's experiment. We assume that switchgrass yields are unaffected by dryness even beyond the point where the Barney et al. study shows catastrophic losses. This assumption credits biorefineries with greater switchgrass supply than they would normally get as a dry spell progresses because, in reality, yields start dropping before dry spells reach extreme lengths. Due to uncertainty in the precise response of switchgrass yield, we choose the most drought tolerant response in order to ensure that we do not overstate our conclusion.

HIGH RESOLUTION SPATIAL ANALYSIS OF WATER AVAILABILITY AND DROUGHTS

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 [34].

Figure 1. Annual Average Precipitation for Kansas from 1971 to 2000 Source: NRCS & OSU PRISM [34]

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 to capture switchgrass yield losses or focus only on assisting with irrigation management. The drought indices most widely used are the Palmer Drought Index [45] and the Koppen climate classifications [46]. However, 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 [37]. A soil dryness index methodology has been applied in Australia that measures daily soil moisture over a season to determine fire management strategies, but does not focus on dry durations but instead observes seasonal effects on soil moisture [47]. 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 [48]. 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 [49]. A similar technique based on spectral imaging was applied to grasslands in the Midwest (Kansas and Oklahoma) and found to accurately measure drought conditions [50]. However, these methods are focused on helping identify when a drought is occurring in order to inform crop management and the use of irrigation and do not enable us to quantify the severity of past droughts.

216 The precise response of switchgrass to water scarcity at its roots has been understudied.
217 However, we do know that a dry spell of seven weeks significantly diminishes harvestable yields
218 [37] and infer that plant yield drops precipitously as each dry spell lengthens. The effect of a
219 series of four 2-day dry spells with rain in between should be less than the effect of a single 8-
220 day dry spell on switchgrass yield. Based on this understanding, we develop a drought index that
221 measures the duration of low soil moisture events on a daily basis with the goal of identifying
222 dry spells and drought severity.

223 We developed our dryness index using high resolution weather and soil data. We integrated daily
224 weather data from 1996 to 2005, obtained from NOAA weather stations and kindly provided by
225 Schlenker [35] including the maximum and minimum temperature, and precipitation on a 4 km
226 grid to estimate inches of water stored in the soil on a daily basis. Rainfall adds to the water
227 level, capped by local field capacity, and evapotranspiration depletes the stored water. We
228 assume that there is no lateral inflow from aquifers. We used U.S. Geological Survey soil data on
229 field capacity and water table depth to calculate the local soil storage capacity [51].

230 Evapotranspiration is calculated by the Hargreaves method, which uses only the maximum and
231 minimum temperature, and extra-atmospheric solar radiation, which we calculated based on the
232 latitude of each grid cell [52, 53]. We assumed an evapotranspiration crop coefficient of 1, which
233 is an average for corn and switchgrass [54].

234 Based on the soil moisture we look for extended periods of drought or “dry spells,” which are
235 periods when the soil moisture is below the Maximum Allowable Depletion (MAD) for a given
236 crop and root depth. Below the MAD a given crop’s roots have difficulty extracting moisture
237 from the soil causing water deficit stress. Additional research is needed to understand a MAD
238 value, or range, for switchgrass. We use a MAD of 50% which is a normative for most crops

[55]. 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 fully reflects the current understanding of switchgrass response to lack of water; longer spells are given a higher weight (time is squared) and multiple dry spells (expected to weaken the crop) are included (four longest dry spells are added). The switchgrass yield losses reported in Barney et.al. [37] corresponds to a value of 2,401 using this drought index. As we discuss earlier, we take a conservative approach and apply the step function loss of harvestable biomass when a region's drought index exceeds 2,500 to ensure that we do not overestimate drought losses. Equations for the dryness index are provided in the supplementary material. We recognize that this direct interpretation of the limited literature is a simplified representation of a highly complex mechanism of plant growth. However, in the absence of better literature for more precise results from drought experiments this methodology is useful in pointing out that droughts can influence biofuel production.

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) are 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 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 2,500. 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 2,500.

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 areas that receive greater annual rainfall on average. For example, the northeast corner of Kansas shows relatively moderate average annual rainfall levels, 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

BIOREFINERY SUPPLY CHAIN ECONOMICS

We model switchgrass production and assume biorefineries are located within the regions studied to minimize transportation costs and we apply a simplifying methodology that assumes

biorefineries are sited at the geographic center of their regional lands³. Biorefineries are sized based on the amount of switchgrass available from CRP lands within each county. Biorefineries have economies of scale meaning that larger biorefineries have lower capital costs per unit of ethanol produced. Our biorefinery cost model is based on cellulosic ethanol process costs and performance estimates found in current and commonly accepted literature [9, 11, 22]. In the storage scenario (Scenario 3), we increased the biorefinery storage capital costs by the percentage of biomass stored (i.e. 10 percent). Although storage is estimated to represent 13 percent of biomass feedstock costs [56], centralized storage and pre-processing could either A) increase estimated total delivered feedstock costs by as much as 50 percent, if sub-optimally designed, or B) reduce total costs by 5 percent if optimally designed [57]. Warehouse capital costs constitute 0.86 percent of total capital costs in the NREL report [12], and increases to 0.94 percent in Scenario 3. Biomass losses during storage could be as high as 13% , or as low as 2% depending on storage methods (e.g, on outside sod, versus inside covered building with concrete floors) [58]. We choose to assume that drought losses sufficiently account for storage losses and do not apply an additional storage loss factor. The biorefinery economic model is described in more detail in the supplemental material.

RESULTS

If the Kansas biofuel industry strives to avoid the use of prime agricultural land and irrigation as preferred by most proponents of sustainable biofuels (i.e. by growing non-irrigated feedstock on marginal land) and takes no measures to mitigate drought risk, the state could produce close to

³ We do not attempt to model the precise locations of CRP lands within regions as this could change over time. Our implicit assumption is that CRP lands are evenly distributed through regions.

12 billion liters (over 3 billion gallons) of switchgrass derived ethanol from its CRP lands in a year with good rainfall (e.g., 1999 had good rainfall and is depicted by the solid dark green line in Figure 4) assuming mature cellulosic biorefinery conversion efficiencies. However, in a year where drought conditions prevail, the same biofuel industry would only be able to produce about half as much ethanol at much higher costs (e.g., 2000 had drought conditions and is depicted by the solid orange line in Figure 4). Unfortunately, drought levels that significantly impact switchgrass yield occurs in 4 of the 10 years in the decade we analyzed (see Figure 5 – years 1996, 2000, 2001, 2002). Considering that biorefineries are typically planned with at least a 20 year life, feedstock disruptions that occur at this frequency will cause major financial shocks to many farmers and biorefineries.

Figure 4. Biofuel Supply Curves from each Scenario

Figure 4 also shows that even when the industry plans for drought by taking the measures we describe in the aggregated and storage scenarios, these do not protect it effectively against cost spikes and supply curtailments. If the industry is composed of large biorefineries who source from a wide hinterland, the production costs are very low in a wet year (dark blue line) but they were still not protected from feedstock shortages in every year of the decade (example, light blue line) because droughts in some years tended to affect substantial portions of Kansas. Storage does provide some protection against drought risk by lowering costs in bad years. This is shown by the difference between the dashed and solid orange lines in Figure 4. However, this benefit in the bad year comes at the cost of curtailed production and higher costs in a good year (the difference between the dashed and solid dark green lines in Figure 4). If a few good years occur

in succession, the management of biorefineries will likely face pressure to justify multiple years of foregone revenue while storing for drought years.

Figure 5. Biofuel Supply Cost Curves for Each Year for Scenario 1

Figure 5 shows that if switchgrass biorefineries had been built in Kansas without planning for drought, they would have faced high production costs and curtailed production in four years during the decade spanning 1996 and 2005. Biorefineries could take emergency loss mitigation measures in drought years like deferring payments on capital but these cannot be sustained if drought induced disruptions occur in 4 years out of 10.

In the storage scenario, biorefineries attempt to mitigate some of the annual switchgrass yield variation by under sizing biorefinery capacity by 10% relative to scenario 1 but still contracting for the same amount of switchgrass from Kansas' CRP lands, leaving surplus switchgrass (i.e. 10% of annual production in a good year) from bountiful harvest years for years of scarcity. As we already discussed above using Figure 4, storage yields benefits when a dry year follows a wet one. However, this strategy becomes problematic when successive drought years occur. Figure 6 presents storage results when 1 wet year (1999) is followed by 3 successive dry years (2000 – 2002). The solid lines in Figure 6 are reproduced from Figure 5 for the years from 1999 – 2002 and the dashed lines are the cost curves for those same years for the storage scenario.

Figure 6. Biofuel Supply Cost Curves for the Storage Scenario and Scenario 1

In the wet year (1999), the storage scenario shows decreased output and increased costs relative to scenario 1 as biorefineries are slightly smaller, and therefore more expensive per unit of

ethanol (due to a loss of economies of scale), and are buying 10% more switchgrass than they consume. 2000 is significantly dryer than 1999 and has less switchgrass available than refining capacity and therefore biorefinery outputs are curtailed and costs are higher in 2000 compared to 1999. Storage narrows these cost and production differences between 1999 and 2000. Unfortunately, 2000 is followed by another dry year, although drought conditions are less severe in 2001, which, in turn, is followed by the driest year in Figure 6 (2002). Most of the benefits from storage are wiped out in 2001 because the excess switchgrass from 1999 is consumed in 2000 leaving very little to carryover to 2001. Droughts do not affect all counties equally. While most counties do not produce enough switchgrass to supply their biorefinery at full capacity in 2001, some do have carryover to 2002. This carryover combined with smaller biorefineries results in better capacity utilization in 2002 which lowers the costs for that year relative to scenario 1.

From 1997 to 1999 and again from 2003 to 2005, biorefineries designed to store switchgrass supply produces less biofuels (2.5% decrease) and the aggregated biorefineries produce roughly the same quantity than would otherwise be the case. However costs are lower by 4% for the storage scenario over the entire decade than in the scenario 1 (although additional storage costs would reduce some of this cost savings). This shows that over contracting by 10% each year does marginally lower costs but does not improve total biofuel production and is not a very good drought risk mitigation strategy, especially if dry and wet years occur in streaks rather than in an alternating pattern. The aggregate scenario reduces costs by 18.8% over the base case due to the larger economies of scale of the biorefineries, but also has similar “good” and “bad” years and therefore does not mitigate against drought effects either.

DISCUSSION

373 Feedstock losses, and the potential economic repercussions, could prove problematic if drought
374 conditions suggested in climate models prevail. Studies predict that climate change will have
375 significant impacts on natural water cycles leading to an increased frequency of extreme weather
376 events throughout the Midwest, including floods and droughts [23-28]. With advancing climate
377 change, many biorefineries planned in the Midwest could face drought induced feedstock losses
378 more than once over their lifetime. Since the probability of at least one feedstock producing
379 region suffering from drought induced losses is higher as we expand the total area of biofuel crop
380 production, aggregate curtailment of supply and higher production costs could occur more
381 frequently. Biofuels energy resources are desirable for mitigating climate change, but what
382 options are available to mitigate the economic vulnerability that a dryer climate could impose on
383 future biofuels industries? We speculate that biofuel businesses focused on producing sustainable
384 biofuels (i.e. sourcing non-irrigated feedstock from marginal lands) not only need to prepare for
385 drought but also need to go beyond the mitigation measures of (1) sourcing feedstock from a
386 wider area and, (2) storing feedstock.

387 Could designing biorefineries to handle multiple feedstocks sufficiently mitigate drought risks?
388 Few of the current and planned biorefineries are designed to receive multiple feedstocks, and a
389 wholesale shift to multi-feedstock plants could introduce additional capital costs, but would this
390 sufficiently insulate the industry from drought risks? Assuming a future where a fully
391 commercial biofuel industry is well established, most feedstocks will already be contracted and
392 dedicated to other biorefineries and therefore unavailable. Thus, we chose to model a biorefinery
393 industry where individual plants are designed to accept a single feedstock for the following
394 reasons. Furthermore, if all biorefineries are multi-feedstock facilities, any drought caused
395 switchgrass shortages will lead the industry to face high costs collectively, due to spikes in spot

396 market feedstock prices. We saw clear evidence of this in the 2012 drought where corn price
397 escalations resulted in biorefineries shutting down [31].

398 Could regional optimization sufficiently mitigate drought risks? Regional planning and
399 optimization to minimizes total costs (including siting locations, non-drought related switchgrass
400 plot yield variations, transportation modes and distances, biorefinery sizes and switchgrass
401 supply aggregation, etc.) will not compensate for feedstock losses during droughts. We anticipate
402 that optimization models would produce similar “relative cost” results as those presented in this
403 paper if droughts curtail feedstocks. Even if an optimized region reduces the entire supply-chain
404 cost of biofuel production, major feedstock losses will still have the same relative effects on
405 production and costs.

406 Are the most expensive biorefineries consistent from year to year? We evaluated the relative
407 ranking of biorefinery across the evaluated timeframe to determine if there are regions that suffer
408 from droughts more frequently than others suggesting that some regions are more risk prone.
409 While it is true that some of the western most counties of Kansas do experience more frequent
410 droughts, droughts affect biorefineries all across the state. Not building the most risky
411 biorefineries would essentially remove the high-cost/low production tails on the biofuel supply
412 curves. This will reduce industry risk at the expense of biofuel resource production. Similarly,
413 biorefineries sizes could be based on a dryer year (as opposed to the wettest year as presented in
414 this paper) with a result similar to our storage scenario; a scenario that reduces the net biofuel
415 output, raise the net cost, and does not insulate the industry from droughts.

416 Will the incorporation of stochastic planning sufficiently mitigate drought risks? Stochastic
417 analysis should be done well in advance of large-scale biofuels development, and would likely

highlight regions that are relatively more drought prone than others. However, the most likely outcome is that some regions are determined to be too risky to justify dedicated biorefineries and their absence would result in a shorter biofuels supply curve. It could be argued that growing feedstocks in risky regions anyway (without building a dedicated biorefinery) could provide feedstock buffers for other less risky regions. Again this is similar to our storage scenario.

Farmers could choose irrigation as their primary drought mitigation option. But this is problematic because studies have shown that irrigation substantially worsens the lifecycle environmental footprint of biofuels [18] and causes other significant negative environmental impacts on water supplies [59]. These effects weaken the environmental goals of policies like the RFS2, the LCFS and the RED. Growing biofuel feedstocks on marginal lands likely means that irrigation infrastructure is not in place. Moreover, many Midwestern states that are expected to be major suppliers of biofuel feedstocks that might also face an increase in drought frequencies in the coming decades, like Iowa, are not prepared to irrigate and this capital cost will raise production costs even in good rainfall years.

Biorefineries and farmers could, and most likely will, purchase insurance against drought-caused losses. Currently, crop insurance typically covers material losses but not labor and other operations losses. However, insurance will mitigate economic losses occurred by farmers and biofuels producers, but will not produce fuels.

Our results should spur the research and development of technologies that help protect against drought losses. It is essential to study the yield response of popular biofuel feedstocks like

switchgrass and miscanthus over a wide range of drought stresses as well as the mechanics of how plants are affected by dry conditions.

Our results have significant implications for fuel policies. They suggest that the fixed annual volumetric biofuel mandates of the RFS2 only be met at very high costs during drought years. This exact scenario played out during the Midwestern drought of 2012 when ethanol prices spiked due to corn supply shortages [31]. In future drought years, the EPA may be forced to waive its mandated targets due to the adverse economic impacts we find. While such a waiver may ease the economic pain, the environmental goals of the policy will not be met. Importantly, policymakers need to recognize that even if cellulosic biofuel technology costs drop as fast as the most optimistic projections these gains do nothing to prepare for the economic risks presented by more frequent droughts. At best, this should raise doubts that biofuels can meet ambitious low carbon fuel policy targets consistently at reasonable costs. At worst, these policies could be branded as failures if their targets are met at high costs or not met at all due to drought-induced waivers..

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Annual Dryness Index (Maximum)

250 500 1000 1500 2000 5000 10000 15000 20000