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Chapter

Drought Impacts on Bioenergy Supply System Risk and Biomass Composition

Amber Hoover, Rachel Emerson, Jason Hansen,
Damon Hartley and Allison Ray

Abstract

Bioenergy is an important renewable energy option worldwide, but the industry is susceptible to a myriad of risks including biomass supply, of which drought plays a role. Crops yields decrease during drought, increasing year-to-year risk for the agricultural industry. For the renewable energy industry, in particular, the effect of drought on crops is substantial and complex. This chapter discusses the current state of knowledge regarding how drought affects biomass destined for renewable energy as it relates to dry biomass yields and chemistry, the latter of which heavily impacts cost of production and final product yields. Advanced supply systems are one option for reducing biomass supply risk. These systems lead to higher, less variable crop yields during uncontrollable events like drought; however, the quality of material supplied in a drought year may still vary as drought impacts plant chemistry. This chapter provides analysis for chemical composition of four bioenergy crops observing that both carbohydrates and lignin decrease during a drought year compared to a year with minimal to no drought. These chemical changes can impact biochemical conversion through inhibitor formation and altering degradability during pretreatment.

Keywords: bioenergy, drought, chemical composition, inhibitors, yield, supply system, biorefinery

1. Introduction

Bioenergy is one of a portfolio of renewable energy options used worldwide to support efforts to decrease use of fossil fuels and support energy security policies. By 2050, the total world bioenergy potential is predicted to meet 25–33% of the world's energy demand [1]. One study estimates that in the U.S., by 2040, more than 1 billion tons of biomass could be available for use in the bioenergy industry; however, the water consumption necessary to support these crops is a clear concern, and recent analyses investigate scenarios with purpose grown energy crops that are assumed to be rain fed rather than irrigated [2]. Energy crops are an important strategy for the emerging bioenergy industry, but erratic environmental factors remain a risk with drought being a major factor affecting crop production, particularly for crops grown without irrigation. Widespread droughts covering 30% of the U.S. have occurred every decade since 1900, and drought frequency has increased

in recent decades [3, 4]. To make matters worse, extreme weather events, like drought, are predicted to become more prevalent under future climate scenarios with corresponding decreases in gross primary productivity [5–8]. The economic impacts of drought are exemplified by the $30 billion in losses from a recent U.S. nationwide drought in 2012 that primarily impacted the agricultural industry as a result of outcomes such as a 27% reduction in U.S. corn grain yields [9]. These yield losses pose considerable risk for biomass producers and biorefineries that already have substantial startup challenges to overcome [10].

Drought conditions lead to increased use of water resources in irrigated areas, but in non-irrigated fields obtaining necessary crop yields is a challenge. Corn, wheat, and barley grain yields have been shown to decrease as a result of drought [11–13]. Of importance to bioenergy technology developers planning to use ligno-cellulosic biomass, dry biomass yields of corn stover, switchgrass, and *Miscanthus* grown in research plots were reduced in the 2012 drought when compared to yields in 2011 and 2013 [14]. Even crops that have been reported to have some level of drought tolerance, like sorghum and switchgrass, had significant yield reductions during drought, 40–80% in some cases, even though the plants often survive the drought stress [15–17].

Drought is a major risk for producers and biorefineries relying on consistent and high crop yields; however, for the renewable energy industry the effect of drought on crops can be even more substantial and complex. The objective of this chapter is to discuss how biomass destined for renewable energy is affected by drought as it relates to overall dry biomass yields and chemistry, the latter of which heavily impacts cost of production and final product quality. The chapter proceeds with a discussion of how drought related risks impact the supply chain and strategies for risk reduction through thoughtful design of logistics systems for biorefineries. Finally, the chemical analysis of a variety of bioenergy crops grown during severe drought conditions as part of a set of long-term nationwide field trials will be discussed along with the state of knowledge regarding how these changes impact conversion to biofuels and products.

2. Reduction of bioenergy industry risk through supply system design

In bioenergy, the risks are as diverse as the economic agents that make up the industry. From the beginning of the supply chain, the risks farmers face are different from the risks aggregators face. Aggregators, the people who harvest, collect, and transport feedstocks to the biorefinery, face different risks than owners and managers of the biorefinery. While some risks in bioenergy apply across these agents, e.g., the risk that a market for the finished product might not exist, the fact that risk is perspective dependent means that one must be precise about whose risks are under discussion. This section considers one type of risk, supply risk, which biorefinery owners and managers face because of the role that drought and weather variability play.

Risk is a concept to measure 'unwanted' events. At the biorefinery, supply risk means that management must engage in unwanted, costly activity if the chance of insufficient feedstock supply delivered to the biorefinery for conversion materializes; thus the plant cannot run at full capacity. Risk is the probability of an unwanted event occurring multiplied by the consequence [18]. For management, this means that if the feedstock supply is lower than the full capacity of the plant then at least two undesirable events are realized [19, 20]. First, the amount of product created at the plant is reduced meaning that the unit cost of production, and the price necessary to cover costs, increases. The plant must utilize the same amount of

resources to run the facility at full capacity as when it runs at less than full capacity, thus driving up unit cost. The second is that, in order to overcome the first undesirable outcome, management must seek out additional sources of feedstock supply. Because the additional supply is not placed under the contract managers have with growers for the initial supply, making up the short fall, too, is costly [20].

Depending on the nature of the risk under analysis, different approaches for mitigation apply [21]. Supply risk is considered non-systematic or diversifiable risk because yield uncertainty is not correlated with risks in other parts of the economic system. For example, crop yield does not correlate with stock market performance but instead with climate variability. For a biorefinery manager, non-systematic risk means that diversification is a strategy to mitigate weather variability. To illustrate how diversifying the feedstock supply allows the manager to mitigate risk, this section proceeds as follows. First, a description of the biomass feedstock supply chain provides a picture of how risk enters the system through yield uncertainty. Then an example illustrates how alternative supply system design enables mitigating supply risk caused by weather events, such as drought.

2.1 Supply chain

Possible biomass supply system configurations are numerous, but are typically classified in two ways: non-distributed and distributed. The non-distributed supply systems, also termed conventional supply systems, have been the systems of choice for the pioneer, or first-built biorefineries [22]. Non-distributed supply systems tend to be vertically integrated with a specific user. This means the biorefinery manages the supply chain from the time the biomass leaves the field to the time it enters the gates of the biorefinery. The materials are delivered in a minimally processed state and the burden of controlling and mitigating feedstock variability is placed on the users at the biorefinery. Non-distributed systems are typically sited in areas with an abundance of easily accessible and low-cost resources. The location of the pioneer biorefineries, as expected, have all been developed in areas with concentrated supplies of biomass known as supply sheds. While supply chains developed using this design are relatively uncomplicated and inexpensive, the biorefineries are limited to a small draw radius, due to the expenses associated with transporting material in the available formats. The relatively small supply shed may impact the ability for the biorefinery operators to mitigate feedstock quality issues with the resources available and potentially not be able to meet resource demands if there is a catastrophic event within the supply shed [23, 24].

The alternative, distributed supply system, sometimes called an advanced supply system, is a series of processing depots or terminals that are used to concentrate material from a small geographic region, near the point of production, and prepare it for use at a single or multiple facilities. This model is similar to how grain elevators work, the grain from local fields is aggregated and sold into a larger market. And, similar to logistics in grain supply systems, the processing depots may be owned by parties other than biorefinery owners. However, instead of simply holding the material for sale, the depots produce a stable, tradable intermediate product, which can be sold in a variety of markets. For a biorefinery, the largest benefit of the distributed supply system is having access to a larger supply shed for material. Biomass quality (e.g., ash and moisture content) is highly variable both spatially and temporally [23]. Through sourcing the material from a series of depots, biorefinery operators are able to specify the desired quality attributes of the material, and the burden of delivering material within the specifications is borne by the owners and operators of the depot. Although the cost of distributed supply systems seems high compared to a non-distributed system, given the

3

requirements for additional infrastructure and increased transportation, system-wide benefits may offset costs [19]. The next section illustrates this point with an example of risk mitigation.

2.2 Mitigating drought risk

Figure 1 illustrates both the distributed and non-distributed, stylized supply chain configurations situated on a map of the Midwest United States. The panel on the left shows the location of a biorefinery and 10 potential sites for biomass depots. Multiple processing depots represent the advanced (distributed) case. The black lines illustrate the supply shed radius, which is the geographic area from which biorefinery management collects feedstock. In the conventional (non-distributed) case, the supply radius is 50 miles and the supply shed consists of fields near to the biorefinery. The dotted, black line next to the biorefinery shows the 50 miles radius. Economically constrained by transportation costs, in the conventional case management must contract with growers in near proximity to the biorefinery. On the other hand, the wider, solid black line encompasses the network of depots in the advanced supply case. Because of preprocessing, the economic constraint pushes the supply radius out to 400 miles, thus significantly expanding the supply shed. This enables management to contract with growers at much greater distance. The heat-map shading shows differing levels of drought intensity; red and orange illustrate greater drought intensity and blue a lesser amount.

The Year-A, Year-B designation in the left and right panels, respectively, shows two possible weather outcomes, generated with historical data. In Year-A the map does not show adverse weather events for either supply shed but in Year-B it shows adverse weather in much of the supply shed for both cases. While in Year-A none of the growers in the 50 miles supply shed experience detrimental impacts to crop yield from weather, in Year-B the growers next to the biorefinery collectively face the same adverse weather. By contrast, and looking at the 400 mile supply shed, growers in the northeast of the supply shed do not experience the adverse weather of much of the rest of the supply shed. A simulation model is a useful, analytic tool to understand how weather variability under these two supply chain configurations affect supply risk at the biorefinery.

Suppose management of the biorefinery in **Figure 1** contracts with growers for residual corn stover to procure feedstock to run a biorefinery with nameplate
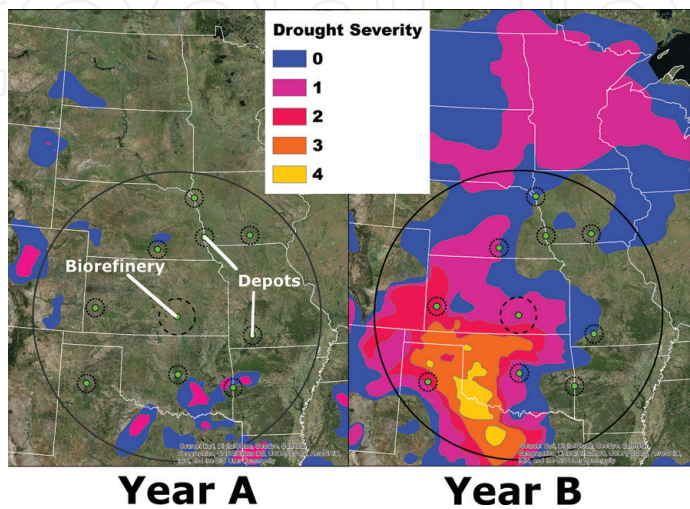

Figure 1.
Comparing two supply chain options under two weather scenarios based on historical data. Year A (left) has no adverse weather events, while year B (right) has moderate to severe drought covering much of the supply shed for both supply chain options [25].
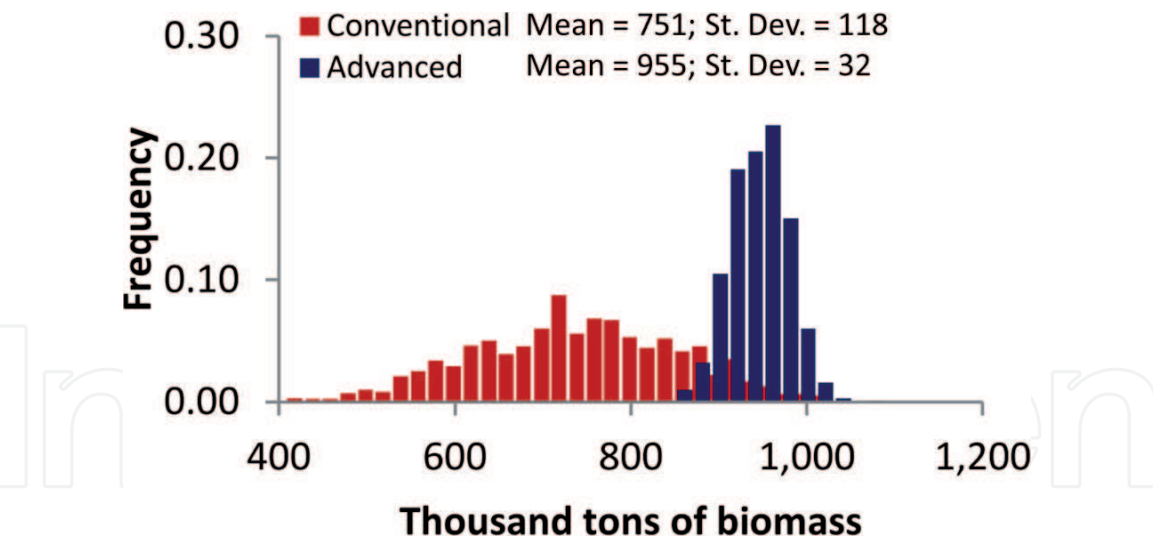
Figure 2.
Histogram of simulated feedstock outcomes under two supply chain configurations [25].

capacity of 800 thousand tons per year. In the conventional case and in the advanced case, management contracts with the same number of growers. In the conventional case farmers face the same distribution of yield uncertainty. In the advanced case the 10 distributions of uncertainty represent 10 separate regions of the supply shed.

Figure 2 shows the histogram of potential outcomes that result from a Monte Carlo simulation of the manager's contract options. The simulation utilizes parameters for yield, ash content, and dry matter loss that are representative of corn stover in the Midwest. The conventional case shows that on average, the manager will receive 751 thousand tons of biomass at the plant, but the range of possibilities extends from as little as 400 thousand tons to just over 1 million tons. In the advanced case, the histogram shows that the manager could expect on average 955 tons of biomass with a range of 800 thousand tons up to 1 million tons.

The results in the histogram illustrate the potential for risk reduction available to the manager by diversifying the supply portfolio. Much like one diversifies a financial retirement portfolio to mitigate risk, advanced supply configurations enable the same strategy. Managers at the biorefinery can mitigate drought-induced supply risk by diversifying the biorefinery's supply portfolio across a larger supply shed.

3. Drought impacts on chemical composition and conversion

3.1 Biomass chemical composition

The biomass supply risks related to drought are substantial and unfortunately extend to biomass quality as well as overall yields as discussed above. Crop yields are often reduced during drought conditions as plants do not have the water needed for basic functions like maintaining cell turgor pressure and performing photosynthesis [26]. The impact of drought conditions on yield as well as plant biochemical functions is complex and different plant types, species, and genotypes may vary in their tolerance and responses to drought [27, 28]. Species like *Miscanthus* are reported to be more sensitive to water deficiencies [29] while crops like sorghum [16], reed canary grass [27], and switchgrass [27, 30] display some level of drought tolerance. In addition, plants use different survival strategies to deal with environmental stressors; for example, there is less carbohydrate hydrolysis in cool-season forbs than in cool-season grasses during osmotic stress that occurs when plants

experience drought requiring plant cell walls to compensate for the external changes in water with solute concentrations [31]. Soluble sugar synthesis in plants has been shown to occur in response to water stress in order to increase osmotic potential with significant accumulation of soluble sugars measured in switchgrass exposed to drought conditions [32].

Complicating reductions in crop yields, plants experience compositional changes during drought; increased extractive components, including soluble sugars, and decreased structural sugars were reported for important potential bioenergy crops like switchgrass, *Miscanthus*, mixed grasses, and corn stover [26, 32–34]. Studies have even observed reduced lignification in some cases possibly resulting from decreased plant growth as well as changes in lignin component distribution in plant cells impacting cell wall degradability [33–35]. These compositional changes can greatly impact yield of bioenergy conversion products from these biomass resources. It should also be noted that if these decreases in lignocellulosic components are compounded with decreases in dry biomass yield the estimated product yield can be even further reduced in drought-stressed crops [33].

To demonstrate the effect of large-scale drought on plant composition, data collected through the Regional Feedstock Partnership (RFP) was analyzed [36]. The RFP completed long-term field trials beginning in 2008 for potential bioenergy crops grown across the U.S. unintentionally providing a unique snapshot of how drought could impact the bioenergy industry when nationwide drought covered 65% of the continental U.S. in 2012 during the field trials [36–38]. Four RFP crops—*Miscanthus*, mixed grasses, switchgrass, and energycane—were selected to examine the impact of drought on plant chemistry. Each crop field site, according the U.S. Drought Monitor [37], experienced a year with drought conditions and a control year with minimal to no drought (**Figure 3**). *Miscanthus*, mixed grasses, and switchgrass data were from 2010, non-drought control year, and 2012, a year with significant drought. *Miscanthus* was located in Saunders County, NE; switchgrass in Day County, SD; and mixed grasses in Ellis County, KS each grown under three nitrogen application levels with three to four replicates. In Tift County, GA, where the energycane field site was located, a drought occurred in 2011 as opposed to 2012, and the non-drought control year used was 2009 as shown in the insets in **Figure 3**. Five genotypes were each grown on three replicate plots for the energycane field site.

Across four crop types, multiple energycane genotypes, and a variety of nitrogen fertilizer treatments, it is clear that biomass from drought years had lower lignocellulosic components than non-drought years, depicted by the differences in glucan, xylan, and lignin greater than zero (**Figure 4a–c**). Glucan was as much as 10% lower for biomass produced during a drought year (**Figure 4a**), while lignin was up to 5.5% lower (**Figure 4c**) and xylan up to 3.5% lower (**Figure 4b**). These differences are hypothesized to result from less lignification during reduced plant growth and increased synthesis of soluble components that support osmoregulation, in favor of synthesis of lignocellulosic components as hypothesized in previous studies [17, 33, 39]. It should be noted that not all research plots included in the analysis had greater lignocellulosic components in a non-drought year (differences less than zero shown by dotted lines in **Figure 4**), which is probably a result of the complex agronomic and environmental factors that can simultaneously impact plant yield and composition. Previously reported results on similar RFP samples indicated that along with the year-to-year variability, including drought and non-drought years, agronomic factors of nitrogen treatment and genotype also significantly impacted biomass yields and sustainability measurements [36]. Future studies are necessary to examine the complexity of the combination of these factors using multivariate analysis techniques that include, but are not limited to, drought. In addition, compositional changes in response to drought in the
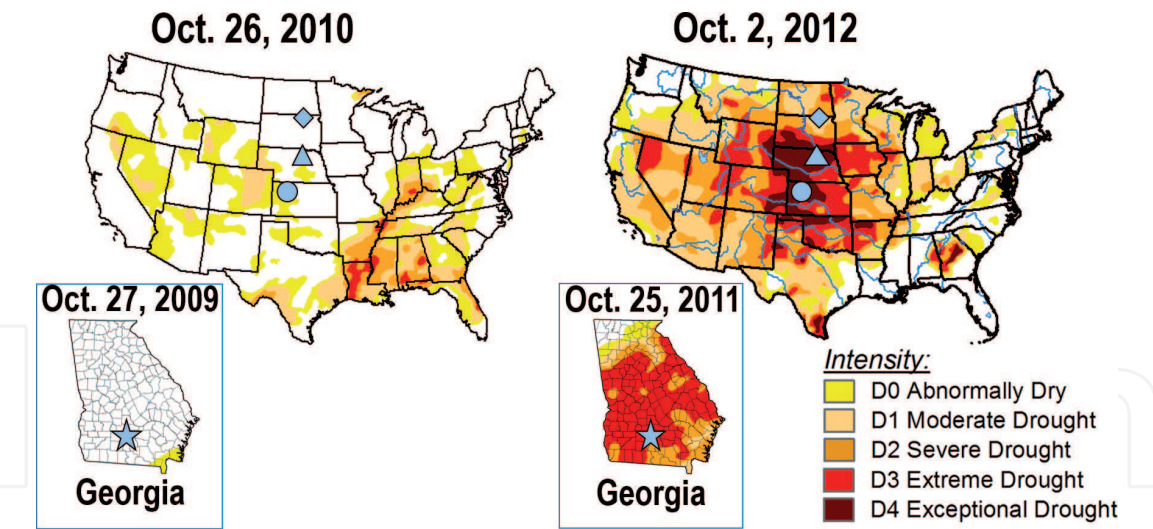
Figure 3.
U.S. Drought Monitor maps displaying continental U.S. drought conditions prior to the time of harvest in October 2010, a year with minimal drought, and 2012, a year with drought conditions covering much of the U.S. The inset displays Georgia drought conditions for October 2009 and 2011. Blue shapes indicate the approximate location of each biomass crop: triangles (▲) for Miscanthus, circles (●) for mixed grasses, diamonds (◆) for switchgrass, and stars (★) for energycane.
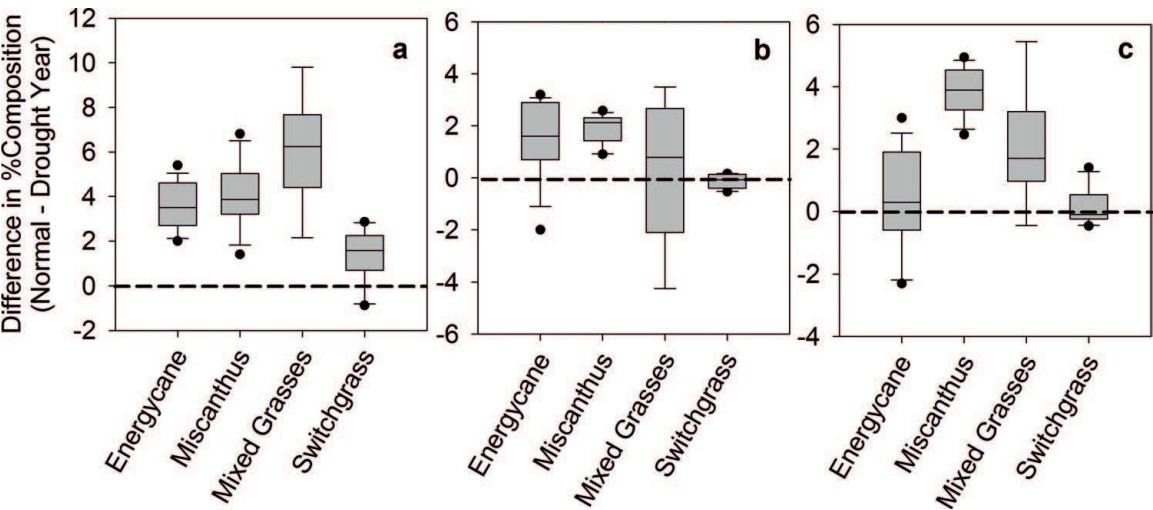
Figure 4.
*Difference between percent glucan (a), xylan (b), and lignin (c) content for four crops grown in a year with minimal to no drought and a year with drought conditions shown in **Figure 3**. Dotted lines represent no difference. Energycane—n = 15, Miscanthus—n = 12, mixed grasses—n = 9, and switchgrass—n = 11.*

literature are mixed. A number of studies report hemicellulose and lignin contents decreasing after drought treatments [33–35, 40], and in contrast other studies report hemicellulose and lignin contents remaining unchanged or increasing under drought conditions [33, 39, 41]. These differences are not completely understood; however, studies have suggested they arise from differences in drought severity and timing [33, 34, 39], genetics [35], and species specific differences [31, 42]. In addition, other environmental parameters like soil nutrient content and texture, timing of precipitation, growing degree days, and optimal growing temperatures also likely play a role.

3.2 Biochemical conversion processes

Drought-induced alterations to plant composition can significantly impact the yield of conversion products. Changes in biomass composition were exhibited by

RFP crops in response to drought stress, where the combined reduction of both structural carbohydrates and biomass yield led to an average 10–15% decrease in theoretical ethanol yield per Mg of dry biomass for *Miscanthus*, corn stover, and mixed perennial grasses [33]. In the 2012 drought year, mixed grasses grown in Kansas had only 10% of the dry biomass yield obtained in the non-drought year and *Miscanthus* dry biomass yield in Nebraska was reduced by an average of 14% [38]. These dry biomass decreases coupled with carbohydrate reductions shown in **Figure 4** severely reduce theoretical product yields. Interestingly, energycane in Georgia and switchgrass in South Dakota did not have dramatic decreases in above-ground biomass yield, which may be due to strong responses to other factors like temperature in the case of energycane, and the reported drought tolerance of switchgrass [38]. Theoretical ethanol yield is often used to demonstrate conversion potential for bioenergy crops based on carbohydrate compositions; however, it is just an estimate of potential yield and is based on assumptions of 100% conversion of carbohydrates to ethanol. In reality, there are many other considerations regarding biomass composition that can affect the pretreatment, enzymatic hydrolysis, and fermentation steps that are necessary to convert biomass to products in biochemical conversion. Hoover et al. [34] reported that *Miscanthus* carbohydrate yields from dilute-acid pretreatment and enzymatic hydrolysis were actually higher in drought affected plants compared to those grown in a non-drought year, which was hypothesized to be a result of higher extractable glucose and lower lignin contents. It is thought that reduced lignin content, observed in some drought-stressed plants, can decrease recalcitrance by creating better access to cell wall carbohydrates and increasing conversion efficiency, but changes in lignin distribution in tissues may also play a role in cell wall degradability in water stressed plants [35, 43]. The increase in carbohydrate yields is not isolated to dilute-acid pretreatment and enzymatic hydrolysis, as drought-stressed *Miscanthus* had increased carbohydrate yields in mild-alkali pretreatment and enzymatic saccharification [39] and after a mild hot water pretreatment and saccharification in nutrient rich environments [28]; in both studies this trend was either less pronounced or not present for leaves when compared to stems. A tall fescue mixture also had few significant increases in carbohydrate conversion yields, thought to be a result of less severe drought growing conditions [34]. A recent report documented increased extractability of pectin components in the cell wall ultrastructure of loblolly pine in response to low soil moisture [44]. Increases in cell wall elasticity have been observed under moisture stress conditions in *Pinus radiata* and may be related to drought tolerance [45]. Pattathil et al. [44] suggested that stress-induced alterations in cell wall elasticity may involve cell wall loosening processes that result from rearrangement of structural cell wall components like pectins and hemicelluloses. Increased elasticity of plant cell walls in biomass may pose further challenges to feeding, handling, and physical/mechanical deconstruction of biomass that is requisite for biochemical conversion. Understanding the changes in cell wall structure, chemical components, and physical properties imparted by drought stress is critical to informing how these properties can be exploited to improve bioprocessing of lignocellulosic feedstocks to biofuels and co-products.

It must also be considered how drought impacts the formation of certain degradation products that decrease conversion efficiencies though inhibition of enzymes during enzymatic hydrolysis and microorganisms during the fermentation step in a biochemical conversion process. For *Miscanthus* pretreated with dilute acid, enzymatic and fermentation inhibitors did not increase, however, this was likely a result of the dilute-acid pretreatment temperatures being lower than those required to form inhibitors [34]. In contrast, fermentation inhibitors were increased in drought stressed switchgrass in a study by Ong et al. [32] where the switchgrass was

chemically pretreated using ammonia fiber expansion (AFEX). Specifically, the increase in soluble sugars formed during drought conditions generated pyrazines and imidazoles in the AFEX pretreatment that inhibited growth of the fermentation organism *S. cerevisiae*. These two studies highlight the need to understand drought impacts on plant biochemistry as well as intermediate and final product yields in order to mitigate these impacts. For example, technology developers in areas that are non-irrigated and prone to drought, either currently or in future climate scenarios, should consider the best pretreatment options for a biochemical conversion process based on the chemical profile of drought-stressed feedstock. In addition, a refiner could tailor pretreatment severity to the chemical composition of the biomass entering a facility to optimize product yields by limiting inhibitor formation with the least reduction in carbohydrate product yields. Future research and development activities might focus on enzyme and microorganism development to better handle inhibitors formed as a result of increased extractive components during uncontrollable environmental conditions. Finally, blending either prior to pretreatment or between different steps in the conversion process could be used to control intermediate or product yields and/or reduce concentrations of inhibitors to tolerable levels [46].

4. Conclusions

Drought is a risk for the bioenergy industry that is likely to increase in future years. Current knowledge and resources regarding drought impacts on crop yields, quality of biomass, and conversion performance can be used for determining research and development directions and mitigation strategies. Weather patterns and water resources are important considerations early in the process of site and feedstock selection for a facility where matching genotypes to conditions can support optimization of yields. Irrigation may be an option in certain cases, but there are implementation costs and water resources may not be an available or sustainable option given that a vast amount of water resources are currently consumed for agriculture. The scenarios in this chapter examine an alternative approach demonstrating that supply system design can reduce supply chain risk related to drought; these advanced supply systems hold promise for future biorefineries. Supply risk associated with drought needs to consider crop yield losses, in addition to biomass chemical changes. Data from a RFP field study of four energy crops, representing a variety of nitrogen application treatments and genotypes, showed how biomass lignocellulosic components—glucan, xylan, and lignin—were lower for a drought year compared to a non-drought year. Current literature was used to describe how drought related chemical changes propagate from the field through the conversion process, and planning and mitigation can be implemented throughout the system to reduce risk to the biomass producer and biorefinery. Drought induced chemical changes can create inhibitors during pretreatment, a step in biochemical conversion processes, that decrease the efficiency of the conversion process, which reinforces the need for careful selection of pretreatment methodology and severity based on location and biomass used. In addition, research and development is necessary for enzyme and microorganism development as well as to fully understand species' specific response to drought and support breeding programs to produce bioenergy cultivars with traits like increased water use efficiency. Finally, an advanced supply system can supply a refinery with more consistent biomass amounts year to year reducing operating risk, but a refinery may still receive feedstock with varying quality, even in a given year. Therefore, in-line techniques to monitor biomass chemistry entering a facility could be used to blend biomass or intermediates to

specifications or adjust pretreatment severity to minimize degradation of soluble components generated during drought stress.

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Notes

Chemical composition data presented in this book chapter are available in the Bioenergy Feedstock Library (bioenergylibrary.inl.gov).

Author details

Amber Hoover*, Rachel Emerson, Jason Hansen, Damon Hartley and Allison Ray
Idaho National Laboratory, Idaho Falls, ID, USA

*Address all correspondence to: amber.hoover@inl.gov

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