Chapter 7

Biomass Feedstock Production Impact on Water Resource Availability

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Introduction

In order to meet increasing biofuel demands agriculture will require greater land and water resources. This will likely necessitate: (1) conversion of existing crop land to grow biofuel crops, (2) changes in other land uses (like forest and pastureland) to grow biofuel crops, and (3) increases in the use of fertilizer and agrochemicals (Uhlenbrook, 2007; USDA-ERS, 2008). Ultimately, all these actions will heighten potential agricultural impacts on natural resources. If local agriculture shifts to biofuel/bioenergy crops that require more than current agricultural water supplies, there is a likelihood of deleterious impacts on limited water resources. To be sustainable, bioenergy production must conserve and protect natural resources, including fresh water.

Fresh water is different from other commodities in that it has no substitutes (Postel *et al.*, 1996). Moreover, only 2.5% of all the water on earth is fresh water. The majority of fresh water, 70%, is stored in polar ice caps and essentially unavailable for human use (UNESCO, 2007). The remaining fresh water, 30%, is held in aquifers, soils, lakes, rivers, and the atmosphere. In 1996, it was estimated that humanity used 54% of the runoff that was geographically and temporally accessible and 26% of the total terrestrial evapotranspiration (Postel *et al.*, 1996). This estimate assumed that freshwater usage for humanity was distributed among many uses including transportation, navigation, industrial consumption, direct human consumption, and food production (Postel *et al.*, 1996). Among these current global uses, water is now being called upon for biofuel production. This reduces availability of an already stretched resource.

Freshwater scarcities have already been reported in many parts of the world (Postel, 2000; Brown, 2003). Further complicating these freshwater scarcities, the world population is expected to increase by an additional two billion people by the year 2030 (United Nations, 1998). Historically, water scarcity has been the subject of lawsuits, conflicts, and wars. Civilizations have risen and fallen because of the availability or lack of water (Sadler and Turner, 1993; Postel, 2001; Montgomery, 2007; Diamond, 2005).

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Water availability has not only directly impacted humans and civilizations, but it has impacted the environment. In many areas of the world, freshwater extraction for agriculture, industry, or cities places at risk the health of aquatic ecosystems and the lives those ecosystems support (Postel, 2000). These ecosystems may be further at risk as bioenergy crop production grows and the demand for fresh water increases. Unfortunately, even today fresh water from many aquifers and river systems is being overutilized to meet societal demands (Brown, 2001; Falkenmark and Lannerstad, 2005). It is projected that these water supplies will be further depleted as both the population and associated fuel consumption increase (Postel, 2000; Brown, 2003).

Thus, it would seem that there are some critical underlying problems if bioenergy development was pursued in the United States and across the globe without very careful considerations of the water resource limitations and their critical connections to ecosystem integrity and sustainability of human food.

In this chapter, we review the potential impact bioenergy production will have on water supplies. We assess the following: (1) climate and weather impact on water supplies for biomass production, (2) water use for major bioenergy crop production, and (3) potential alternatives to improve water supplies for bioenergy.

Climate and Weather Impact on Water Supply

Climate Change

Climate change is likely to impact agriculture and food security across the world (Slingo *et al.*, 2005). Climatic variability such as that from El Niño has already had large impacts on crop production. Slingo *et al.* (2005) reported that in future climatic change scenarios, critical temperature thresholds for food crops will be exceeded with increasing frequency. Long *et al.* (2005) concluded that major agronomic crops grown in carbon dioxide enrichment chambers may have significantly overestimated reported yields. Based on their findings, they reported current projections in future global food security are overoptimistic. Meza and Silva (2009) used simulation modeling to analyze maize and wheat production changes with climate change. They estimated that climate change may result in 5–10% reduction in yields of both maize and wheat. Alternative adaptation strategies, such as changing planting dates, could be implemented to help counterbalance the impacts of ensuing warmer and drier environment.

The US Office of Technology Assessment (U.S. Congress, Office of Technology Assessment, 1993) in the report "Preparing for an Uncertain Climate Volume I" discussed the wide-ranging impacts that climate change would have on all sectors of the economy. The report recognized that agriculture would be sensitive to changes in climate and climatic variability. While climatic change impacts may be offset by intensive management over short time frames, agricultural productivity would be at risk with increasing temperature and more frequent droughts. Agriculture's use of scarce water resources for food production during drought periods could become increasingly contentious with urban, industrial, and environmental sectors.

The Western United States is probably the most recognizable area of the country impacted by climate changes. In particular, Western US agriculture is highly dependent on surface runoff for water supplies. Mote (2006) reported that in the Western US river basins, snow was the largest component of water storage. In testimony before the US Congress, Mote (2007) reported that about 70% of annual water flow is from snowmelt and that snow provides roughly a half-year delay in runoff. Water supplies in the Western United States would be highly vulnerable to any climatic changes that influence snowpack. Barnett *et al.* (2005) reported that over one-sixth of the world's population relies on glaciers and snow packs for their water supply, and that the hydrological changes due to climatic change for future water availability are likely to create severe consequences.

Hamlet *et al.* (2007) studied Western US trends in runoff, evapotranspiration, and soil moisture. They found over the last century, runoff had occurred earlier in spring primarily due to increasing midwinter temperatures. These earlier spring runoff events resulted in earlier spring soil moisture recharge. These earlier trends also corresponded with a shift in evapotranspiration from midsummer to late spring and early summer. Combined, these shifts in runoff, evapotranspiration, and soil moisture require adaptations in water management and cropping systems.

Climatic Variability

Agricultural adaptation to changing climatic conditions will depend on how climate change affects the variation of temperature and precipitation (Negri *et al.*, 2005). Negri *et al.* (2005) estimated the effects of climatic variability on US irrigation. They reported that higher temperatures and less rainfall would increase the need for irrigation. Yet, any increase in irrigation to adapt to climate change would be constrained by water availability. Water availability is the primary factor in present irrigation capacity and would likely be much further limited under future climatic change and the increased production of biomass for biofuels.

Kangas and Brown (2007) studied the spatial and temporal characteristics of drought and pluvial events from 1895 to 2003. They observed that the largest annual droughts or pluvial events occurred more frequently in the Central United States. The Western and Eastern United States had a higher percentage of extreme events. They found that of four large pluvial events occurring in the United States during their study period, three occurred during the past 30 years.

In 2008, the major maize producing states of the upper Midwestern US (e.g., Iowa) experienced extreme flooding due to excess rainfalls over an extended period of weeks. This flooding affected early-season planting operations. Previously in 1993, a more widespread area of the Midwest was affected by similar floods. Both events exceeded the historical 100-year return interval.

Additionally, floodwater has the potential for enormous impacts on downstream water quality. The National Research Council (NRC, 2008) reported on the potential impacts of excess nutrient runoff on water quality. They reported that crops with the greatest nutrient inputs would have the greatest potential for impacting water quality. During periods of excess rainfall, there is potential for the flooding of wastewater treatment lagoons in Iowa and their impact on downstream water quality (Simpkins *et al.*, 2002). Not only would flooded soils delay crop production, but excess nutrients in the water could also deteriorate water quality. Strategies would be needed to reduce nutrient losses while maintaining productivity.

Drought and subsequent reduced production could greatly impact the biomass available for bioenergy production. Woodhouse and Overpeck (1998) analyzed Central US drought through reconstructed climatic data for the last 2000 years. They used current land-use practices (increased cultivation of marginal lands and the escalated groundwater usage from the Ogallala Aquifer) along with Global Climatic Model predictions. They found numerous pre-1900 droughts eclipsing those of the 1930s and 1950s. Some droughts prior to the 1600s had longer multidecadal durations and greater spatial extent than those of the twentieth century. A study using global coupled climate models (Meehl and Tebaldi, 2004) showed a distinct geographical pattern for recent heat waves in North America and the models predicted more frequent, more intensive, and longer lasting events in the second half of the twenty-first century. Whether from preindustrial, geophysical, or current hypothesized climate change, the Central United States has been and will continue to be vulnerable to droughts and weather extremes. Furthermore, Seager *et al.* (2009) reported that historic tree-ring records from the Southeastern United States show that the twentieth century has been moist from the perspective of the last millennium and free of long and severe droughts that were abundant in previous centuries. Historically, the tree-ring records show a 21-year-long uninterrupted drought in the mid-sixteenth century, a long period of dry conditions in the early- to mid-nineteenth century and that the southeast was also affected by some of the medieval megadroughts centered in the Western United States.

Like many other areas of the world, the United States has recently had extended droughts affecting various areas of the country. While there are too many weather-related droughts to address individually a few that would have a potential impact on future energy crop production can be highlighted. Izaurralde *et al.* (2005) reported that the temperate and subtropical Southeastern United States had the potential for maximum annual biomass net primary production growth rates. The Southeastern United States has one of the highest renewable water supplies in the United States (Solley *et al.*, 1998; Figure 7.1). However, the region is not immune to

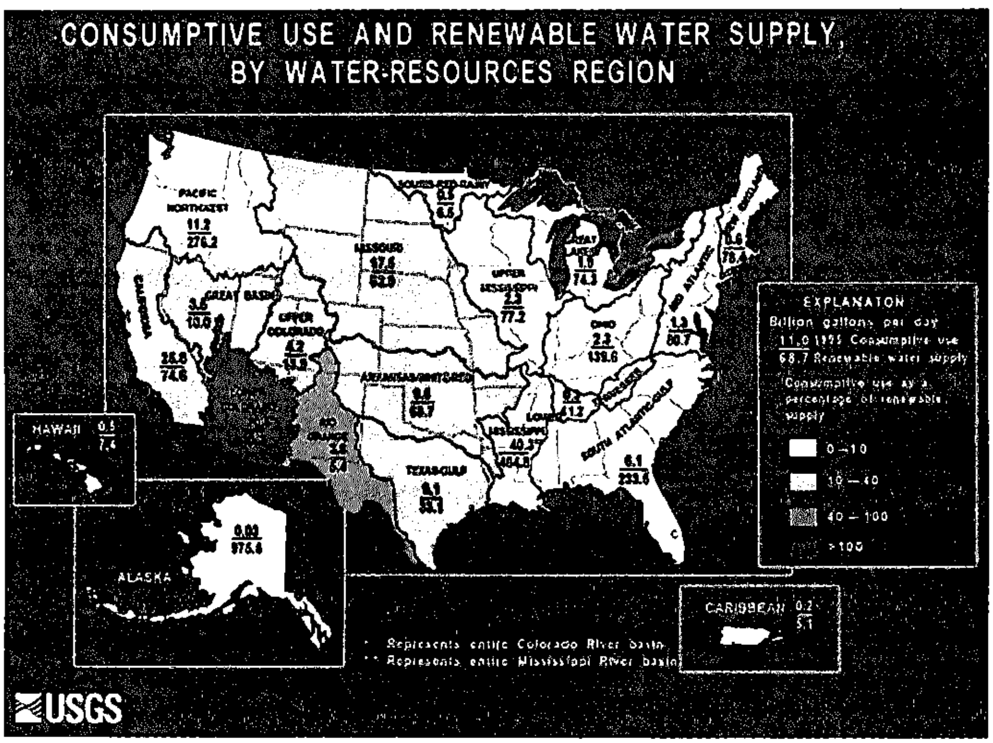

Figure 7.1. Comparisons of average consumptive use and renewable water supply for the 21water-resources regions of the United States, Puerto Rico, and US Virgin Islands. Adapted from USGS 1995 (http://water.usgs.gov/watuse/misc/consuse-renewable.html). For color detail, please see color plate section.

dramatic climatic extremes. A recent multiyear period with intermittent drought in the Southeastern United States caused serious water shortages in the region. The 2007 Southeastern drought was historic and had record high temperatures (Heim *et al.*, 2008). The drought started in December 2006 and expanded with time, with more than two-thirds of the region in drought from midsummer 2007 through the end of the year. Additionally, unusually warm temperatures and scarce rainfall exacerbated conditions. Many Southeastern states (Kentucky, Tennessee, Alabama, Georgia, South Carolina, and Florida) had a record warm August. The cumulative effects of the drought resulted in the driest year in the 113-year record for North Carolina, second driest for Tennessee, third driest for Alabama, and fourth driest for Georgia. In five southeastern states, the governors declared water conservation measures and drought disasters, or states of emergency. The multiyear drought period also led to the imposition of restrictions on water use and opened up legal conflicts within and between states on the regulation and use of the region's water resources (Seager *et al.*, 2009). Alabama and Florida successfully sued Georgia over withdrawing water from Lake Lanier, the main source of drinking water for the Atlanta metro region (Manuel, 2008). Lake Lanier feeds the Chattahoochee River, which supplies water to towns in Alabama and Florida, and whose flow is key to the survival of a host of endangered species such as freshwater mussels and sturgeon. The three states have feuded since 1989 over how to divide the water, but the drought has worsened the problem as the various parties fight over a much-reduced volume of water.

The water restrictions have also impacted agriculture. To reduce water use during declared droughts, farmers in Southwestern Georgia would be paid not to irrigate crops in order to maintain base stream and river flows exiting the state (USA Today, 2002; GA-DNR, 2008). Similarly, in another major agricultural region of the United States, farmers in Nebraska were paid not to irrigate along the Republican and Platte Rivers. This was also a result of multiyear drought conditions (NE-DNR, 2005; US-Water News Online, 2005; NE-FSA, 2007). Although these reductions in irrigation in the Southeastern and Midwestern United States are troubling for agricultural production, irrigation reductions are more common in the Western United States. In many Western US states, cities have purchased water rights from farmers to meet urban and industrial needs (Brown, 2003). These droughts throughout the United States have highlighted the delicate balance that faces agricultural production in competition with urban, industry, and environmental water uses. The competition for water will only be exacerbated by the energy crop production.

Water Limitation Impacts on Bioenergy

As can be seen in the previous section, climatic variability resulting from flooding, droughts, and the timing in water availability can have a tremendous impact on both crop and biomass production. To examine the potential impact climatic variability would have on bioenergy derived from biomass, Eaves and Eaves (2007) used historical data to estimate the supply risk of ethanol (as an automotive fuel) relative to imported petroleum. They compared historical maize production data (1960–2005) with oil imports to determine the relative reliability of ethanol as an automotive motor fuel. Their analysis fitted distributions to both annual maize yields and yearly oil imports. They found through analyzing the distributions that variations of oil imports were less than half those of annual maize yields concluding that maize production was more volatile than oil imports. Most of this increased volatility of maize and ethanol production was attributed to their dependency on weather. Based on their historical analysis, they surmised that displacing gasoline with ethanol would be exchanging geopolitical risk with yield risks.

All climate change predictions point toward increased variability in both temperature and rainfall extremes. If these extremes were incorporated into the Eaves and Eaves (2007) model, increased variability in grain production would be expected. Climate change is predicted to have significant impacts on agricultural production in the future. Many of these changes have been researched relative to their impact on food productivity (Slingo *et al.*, 2005). Climate change will also impact the productivity of biomass and bioenergy crops. These impacts need to be identified and incorporated into decisions related to bioenergy production. Additionally, Elcock (2010) investigated the potential impact of domestic energy production (fossil and renewable fuels) targets may have on future water demand. He estimated that water consumed for energy production would be expected to increase by nearly 70%, and water consumed for biofuels' (biodiesel and ethanol) production is expected to increase by almost 250%. Most of the increases would be for irrigation in the West North Central region of the United States. Increased water consumption could be significant and contribute to localized unintended impacts on water resources. Future biofuel production locations should be evaluated for their potential impacts on local water resources.

Water Use for Major Bioenergy Crops for Ethanol

Traditional agriculture for food and fiber production is the largest user of fresh water throughout the world. The FAO (2008) estimated that agriculture is using a global average of 70% of all freshwater withdrawals from rivers, lakes, and aquifers. In the United States, it is estimated that agricultural water consumption for irrigation is 80% of the total water consumed (Solley *et al.*, 1998). Currently, the two major crops used for ethanol production are sugarcane and maize in Brazil and the United States, respectively. These crops were analyzed and compared as currently managed to determine their relative water utilization during the production of the biomass feedstocks.

Sugarcane Production in Brazil

Brazil is recognized as the world's second largest producer of ethanol (DOE-EIA, 2007; Trostle, 2008). It began promoting the production of crops for ethanol in the mid-1970s after the first global energy crisis (Rother, 2006). Within 10 years, more than three-quarters of cars made in Brazil were able to run on ethanol. The primary crop that Brazil uses for ethanol production is sugarcane. Brazil is the world's largest producer of sugarcane (FAO, 2008: 420 121 000 metric tonnes). Sugarcane is a tall perennial grass native to warm temperate to tropical regions of the world. It has stout, jointed, fibrous stalks that are rich in sugar and measure 2–6 m tall. Sugarcane's high concentration of sugar, which is readily available to microorganisms, makes it uniquely suitable for ethanol production.

Water use in the production of ethanol can be divided between crop production and ethanol production. The water requirement for sugarcane production is approximately 8–12 mm $tonne^{-1}$ of cane production. The sugarcane growing season is year round, and the annual requirements for sugarcane production are approximately 1500–2500 mm yr^{-1} (Moreira, 2007; Goldemberg *et al.*, 2008). The majority of the sugarcane plantations in Brazil rely on rainfall complemented by partial ferti-irrigation, carried out mainly to manage water wastes. Most plantations limit their production to regions where reasonable rainfall occurs (Moreira, 2007). Therefore, irrigation use in Brazil for agricultural production is generally small. However, due to the increasing demand for ethanol and the high prices paid for it, sugarcane production is expanding to regions where irrigation would be needed to complement rainfall (Goldemberg *et al.*, 2008).

In these cases, Moreira (2007) reported that irrigation can be economically feasible, especially using more efficient application methods such as drip irrigation. In Brazil, traditional surface irrigation accounted for approximately 50% of the total irrigation. This surface water application efficiency is fairly low (~61% on average). New production areas could make use of more efficient irrigation application systems.

Moreira (2007) reported that there is generally sufficient water to supply all foreseeable long-term water requirements of Brazil as a whole, but local water shortages can occur as a result of the occurrence of various water using sectors (competition between industry, agriculture, and urban use). Fortunately, the Pacific Institute (2008) reported that Brazil had the largest annual renewable freshwater supply in the world (8233 km^3 yr^{-1}).

The processing and converting of sugarcane to ethanol requires large amounts of water and is the second major use of water in Brazil. Water is used in four major processes: cane washing, condenser/multijet in evaporation and vacuum, fermentation cooling, and alcohol condenser cooling. In 1997, it was calculated that the water use in processing was approximately 21 m^3 $tonne^{-1}$ of cane. However, Macedo (2005) reported that most of the water used in the processing is recycled. Improvements in efficiencies in the production processes have reduced the consumption of water from 5.3 m^3 $tonne^{-1}$ in the 1990s to reported values for 2004 of 1.83 m^3 $tonne^{-1}$ (Goldemberg *et al.*, 2008).

Maize Production in the United States

In the United States, the current major source of ethanol production is maize. This is expected to increase while the industry develops new methods for producing bioenergy. In 2007, the National Corn Growers Association (NCGA) estimated that 24.7% of the US domestic maize went into ethanol production (see Figure 7.2). This was an 18% increase from only 7% in

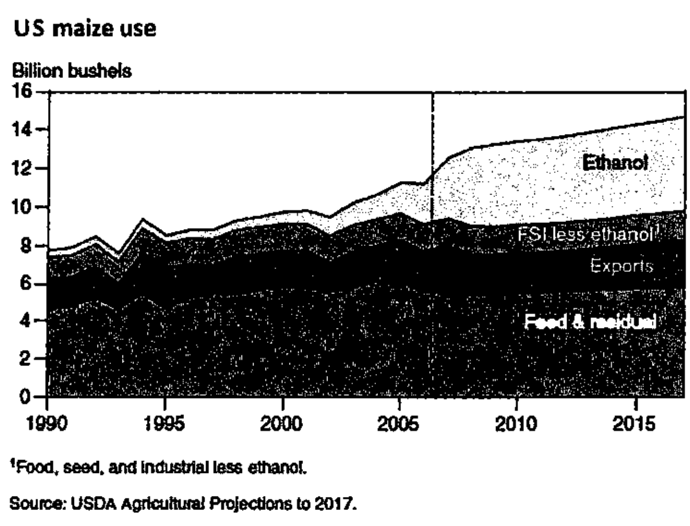

Figure 7.2. Projected U.S. Maize Use from USDA-Economic Research Service (ERS), 2008. For color detail, please see color plate section.

Table 7.1. Top ten maize producing states from the 2002 Census of Agriculture (USDA-NASS, 2004) and 2008 National Agricultural Statistics Service (NASS, USDA-NASS, 2008).

		2002 Census of Agriculture					
Geographic area	2008 NASS Area (ha)	Number of farms	Area (ha)	Number of irrigated land farms	Irrigated land area (ha)	Total area irrigated (%)	Rank in irrigation
United States	34,795,681	348,590	27,611,913	34,278	3,929,446	14	
Iowa	5,382,319	52,806	4,759,666	416	34,909	1	17
Illinois	4,896,696	41,032	4,347,452	913	85,456	2	6
Nebraska	3,561,234	23,889	2,972,301	14,448	1,823,343	61	1
Minnesota	3,116,079	31,782	2,653,152	973	72,219	3	9
Indiana	2,306,708	24,156	2,073,322	767	72,967	4	7
South Dakota	1,922,257	11,446	1,280,907	717	49,869	4	14
Ohio	1,335,463	23,898	1,161,428	26	1,371	0	39
Wisconsin	1,537,805	29,021	1,158,223	501	33,833	3	18
Missouri	1,133,120	15,655	1,083,542	970	99,680	9	5
Kansas	1,558,040	9,552	1,009,358	3,328	545,033	54	2

2001. Although these figures make it appear that a large tonnage of the US maize crop was being diverted into the production of ethanol and away from other uses, the overall impact was offset by increases in maize production and storage drawdown (Trostle, 2008). All other uses of maize have remained approximately unchanged (2001–2007), except for a small decrease in maize exports.

In the United States, the vast majority of maize is produced in the Midwestern states (Table 7.1, USDA-NASS, 2004). Many of the maize producing states (Iowa, Illinois, etc.) have adequate annual rainfall associated with deep rich soils, with adequate water holding capacity to produce maize without supplemental irrigation. However, other maize producing states in the Midwest and High Plains utilize considerable irrigation to produce maize (Table 7.2, e.g., Nebraska, Kansas). Here, the major source of irrigation water in the High Plains region is the

Table 7.2. Top ten irrigated maize producing states from the 2002 Census of Agriculture (USDA-NASS, 2004) and 2008 National Agricultural Statistics Service (NASS, USDA-NASS, 2008).

		2002 Census of Agriculture					
State	2008 NASS Area (ha)	Number of farms	Area (ha)	Number of irrigated land farms	Irrigated land area (ha)	Total area irrigated (%)	Rank in maize production
Nebraska	3,561,234	23,889	2,972,301	14,448	1,823,343	61	3
Kansas	1,558,040	9,552	1,009,358	3,328	545,033	54	10
Texas	930,777	5,102	734,731	1,691	266,355	36	12
Colorado	505,857	1,991	286,597	1,845	256,577	90	16
Missouri	1,133,120	15,655	1,083,542	970	99,680	9	9
Illinois	4,896,696	41,032	4,347,452	913	85,456	2	2
Indiana	2,306,708	24,156	2,073,322	767	72,967	4	5
Michigan	971,246	13,613	812,213	857	72,949	9	11
Minnesota	3,116,079	31,782	2,653,152	973	72,219	3	4
California	271,139	592	68,130	592	68,065	100	29

Ogallala Aquifer. In Nebraska, it is estimated that 95% of the total groundwater withdrawals for irrigation is from the Ogallala Aquifer (Maupin and Barber, 2005).

The Ogallala Aquifer underlies approximately 45 Mha in parts of eight states—Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. The water from the aquifer was initially tapped around 1900. The Ogallala Aquifer is also the major regional source of water for municipal and industrial users. Starting with the Dust Bowl in the 1930s, the occurrence of repeated droughts along with the widespread installation of irrigation systems, water levels in most regions of the aquifer have declined dramatically. The water stored in the aquifer is generally referred to as geologic water because it is generally thought that rainfall takes hundreds or thousands of years to reach low-permeability areas in the aquifer which impede downward water flows to the water table (Andrews *et al.*, 1999). This slow recharge coupled with large water consumption has resulted in declining water tables over most of the aquifer.

The High Plains Aquifer states are some of the top maize producing states. Nebraska was the third largest maize producing state (3.6 Mha), with Kansas, Texas, and Colorado also producing over 0.5 Mha each (NCGA and NASS data). USDA-NASS (2004) estimated that 19% of all irrigation in the United States was for maize production. The USDA-NASS (2004) also estimated that the states overlying the High Plains Aquifer (Nebraska, Kansas, Colorado, and Texas) accounted for approximately 90% of irrigated US maize acreage (Figure 7.3).

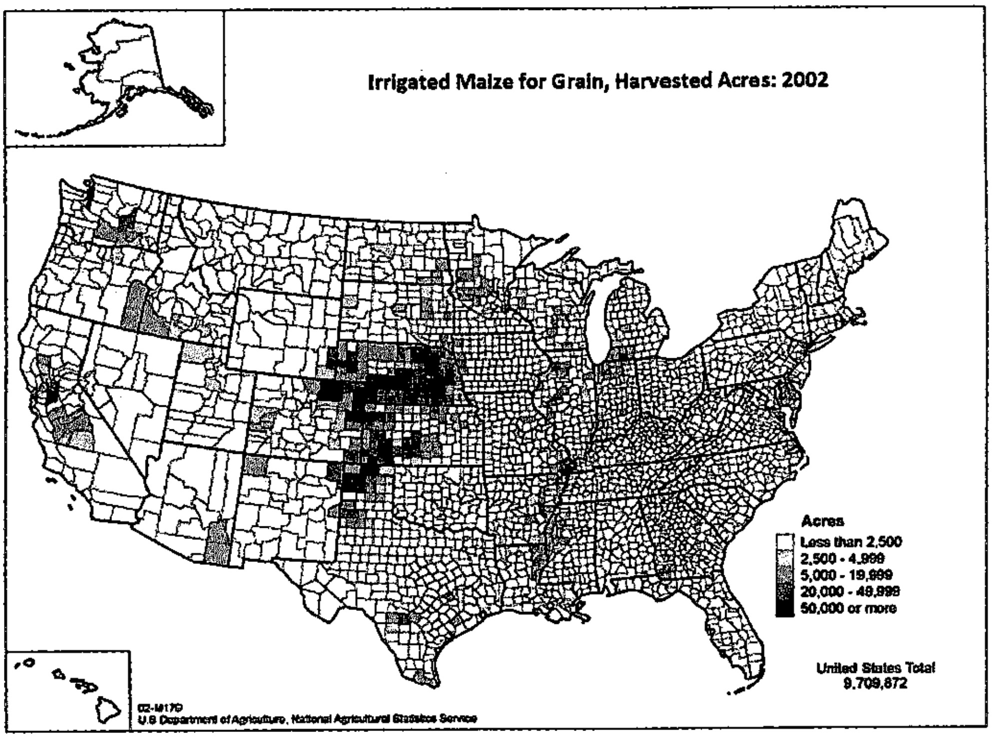

Figure 7.3. US Irrigation maize for grain (http://www.agcensus.usda.gov/Publications/2002/Ag_Atlas_Maps/Crops_and_Plants/index.asp). For color detail, please see color plate section.

Table 7.3. Comparison of water requirements for ethanol production from maize grain, sugarcane, and other potential energy crops.

Crop	Water requirements (m^3 water Mg^{-1} crop)	Biofuel conversion (l fuel Mg^{-1} crop)	Crop water requirement for biofuel (m^3 water Mg^{-1} fuel)	Crop water requirement per unit energy (m^3 water GJ^{-1})
		Ethanol		
World maize (grain)	833	409	2580	97
World sugarcane	154	334	580	22
Nebraska maize (grain)	634	409	1968	74
Maize stover	634	326	2465	92
Maize stover + grain	634	735	1093	41
Switchgrass	525	336	1980	74
Grain sorghum	2672	358	9460	354
Sweet sorghum	175	238	931	35
		Biodiesel		
Soybean	1818	211	9791	259
Canola	1798	415	4923	130.2

Source: World Maize and sugarcane estimates from Postel (1998); Nebraska maize estimates from Nebraska Maize Board (2008); Soybean and grain sorghum (FAO, 1991); Sweet sorghum (Bennett and Anex, 2008; Mastrorilli *et al.*, 1999); Canola (Bauder, 2009); and Switchgrass (Robins *et al.*, 2009; Wright, 2007).

In Nebraska, irrigated maize averages 70% of the total maize acreage (Nebraska Maize Board, 2008, and Table 7.2). In 2007, the Nebraska Maize Board (2008) reported average maize yields of 10 Mg ha^{-1} (160 bu ac^{-1}). The mean 2007 maize yield from Nebraska of 10 Mg ha^{-1} would require approximately 635 mm (~25 in.) of water. Combining the yield with the water requirements for the production would result in approximately 635 m^3 water Mg^{-1} grain. If this is combined with a maize to ethanol conversion rate of 25.9 l ethanol Mg^{-1} grain (2.5 gal ethanol bu^{-1} maize), it would result in a ratio of 1968 m^3 water Mg^{-1} (or 1553 m^3 water/m^3) ethanol. In most of the nonirrigated maize producing areas, the water would be from rainfall and moisture stored in the soil. In irrigated maize production regions such as Nebraska, the NASS reported that the average irrigation for maize production was 365 mm (1.2 ac-ft). This irrigation water requirement would be approximately half of the water needed for maize production. Most of this water in the region would come from the High Plains Aquifer that is already experiencing rapidly declining water levels.

Comparison of Sugarcane and Maize Water Usage

For comparison of maize water use for ethanol production with sugarcane, we used the world average production estimates for sugarcane and maize grain from Postel (1998). We calculated and contrasted the estimates for water requirements for crop production to produce ethanol (Table 7.3). Ethanol conversion from biomass to ethanol was estimated per Mg of maize grain and sugarcane, as 409 and 334 l of ethanol, respectively (James, 2008; US-DOE, 2008). The resulting calculated water requirements were 2580 m^3 water Mg^{-1} (2036 m^3 water/m^3) ethanol for maize grain and 580 m^3 water Mg^{-1} (458 m^3 water/m^3) ethanol for sugarcane. They are also photosynthetically very different. The water requirements to produce maize grain were much higher than water required for sugarcane. The main reason for the greater water requirements for maize grain was that only grain is currently utilized for ethanol production. As new technologies for cellulosic conversion of biomass for ethanol production are discovered, the relative difference between the crop water requirements will be reduced. However, the amount of maize biomass that can be used is limited by soil resource issues such as erosion and nutrient depletion (Doran *et al.*, 1984; Mann *et al.*, 2002; Wilhelm *et al.*, 2004). Again, the large disparity was mainly due to only grain being utilized for ethanol production with maize. Additionally, maize has a much shorter growing season than sugarcane. This shorter growing season with higher water demands and temperature/pollination vulnerability makes maize grain production vulnerable to the following: short-term droughts, lack of supplemental water supplies for irrigation, or excess water from floods. This vulnerability has been previously described with the citation of Eaves and Eaves (2007).

Water Demands for Billion-Ton Vision

Reports by the US Departments of Energy and Agriculture entitled "The Technical Feasibility of a Billion-Ton Annual Supply of Biomass Feedstock for Bioenergy and Bioproducts Industry" (US-DOE, 2005) and "U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry" (US-DOE, 2011) estimated the "potential" biomass within the contiguous United States for bioenergy production. The reports did not directly address the water resource requirements for the Billion-Ton Visions. It assumes that sufficient water resources would be available for increased crop and biomass production. A component of the report focused on the potential for increased grain production for biofuel production.

The US-DOE (2011) study estimated that the US agricultural lands could increase maize production from 27 million dry tonnes in 2012 to 80 million dry tonnes in 2030 at a simulated farmgate price of $40 per dry tonne. These estimates are slightly different from that of a 2005 report as the 2012 update estimated the maize crop availabilities at farmgate prices up to $40, $50, and $60 per dry tonne. Although the 2012 report included the consideration of managing soil carbon during crop residue removal and the irrigation limitation for energy crops especially in western states, the 2012 update still assumed that adequate water resource would be available for maize production to support the Vision. If we assume the same water demands as that for Nebraska maize (634 m^3 H_2O/Mg maize), the Vision currently requires 1.89×10^{10} m^3 (15.3 million ac-ft water), and 5.59×10^{10} m^3 (45 million ac-ft water) by 2030. This is approximately a threefold increase in water demand for production to meet the goals in 2030. Even if geneticists obtained a doubling in water use efficiency to complement the increased yields, the amount of water needed to produce the increased grain would put tremendous stress on current water resources. Alternative cropping and water management approaches must be implemented to meet the Billion-Ton Vision.

Potential Alternatives

Solving our needs for renewable energies while preserving our water resources is an extremely complex problem and will require innovative thinking and adaptation. Researchers throughout the United States and the world are aggressively addressing the issue. In this section, we offer a few examples that could be implemented to address some of the interconnected problems of water and bioenergy and assess their impact.

Crop Production Alternatives and Impact of Cropping Shifts

Karp and Shield (2008) reported on the challenge of producing bioenergy from plants and sustainable yields. They reported that bioenergy from plants, particularly perennial grasses and trees could make substantial contributions to both mitigating climate change and increasing biofuel supplies. The focus of their report was yield traits of key bioenergy crops. They targeted specific traits in these crops for future improvements. From their studies, a common theme was apparent. It was a well-known and very true reality—production of all biomass crops depends greatly on water. Their concluding topic for future work was "*increasing aboveground biomass without increasing water use*." Biomass yields from most of the commonly discussed bioenergy crops (row crops: maize, wheat, etc.; perennial grasses: switchgrass, *Miscanthus*, etc.; and fast-growing trees: poplar, willows, etc.) were all identified as being highly susceptible to shortages of water.

On the other hand, sweet sorghum has long been recognized as a potential sugar crop and more recently for ethanol conversion (Prasad *et al.*, 2007). Sweet sorghum has greater water use efficiency, is more drought tolerant, and requires only 36% the nitrogen fertilizer required by maize. Additionally, sweet sorghum has shown potential for ethanol production due to its rapid growth and early maturity.

Care must be used if major shifts in crop production are implemented without considering the potential changes in water usage. While shifts among crops with similar water usages will have little impacts on water resources, shifts to crops requiring a significant increase in water usage can dramatically impact water supplies. Farley *et al.* (2005) reported that shifting from grasslands to forest could reduce runoff and intensify water shortages. Jackson *et al.* (2005) reported on water impacts of trading water for carbon with biological carbon sequestration. Their study highlighted the potential impacts of introducing tree plantation strategies without considering the full environmental consequences, particularly on water availability. They combined field research with climatic and economic modeling to document substantial losses in stream flows with afforestation. They reported that over the life of the forest plantation, stream flows decreased globally by 53% annually with 13% of streams drying completely for at least 1 year. Powell *et al.* (2005) found a mature forest under varying annual rainfall consumed approximately 85% of annual precipitation. Buytaert *et al.* (2007) reported that converting from natural grasslands to pine plantations resulted in an increase of 40–70% in evapotranspiration.

Reijnders (2006) reported that freshwater resources were not well addressed in previous estimates of biomass for energy potentials. He reported that expanding biomass-for-energy production may substantially exacerbate the world's already scarce water resources for food production. He also pointed out the use of short rotation trees and woody crops consume considerable water and that water availability should be considered as major criteria for site selection. In Mississippi, the unintended impact of large-scale crop conversion was reported by Welch *et al.* (2010). Due to the demand for biofuels and commodity prices, maize acreage increased 288% in the Mississippi Delta along with a concurrent 47% decrease in cotton acreage. This shift to maize production has had implications for both water quantity and quality in the Delta. This includes the loss of cotton seed as a significant accumulator of available soil nitrogen (Hunt *et al.*, 1998). They reported accelerated water-level declines in the Mississippi River Valley alluvial aquifer. Additionally, they estimated through simulation that increased nitrogen fertilizer for maize production will likely result in increased nitrogen export. They concluded that shifting from cotton to maize production may further contribute to the hypoxic conditions in the Gulf of Mexico.

Using Treated Agricultural Effluent for Bioenergy Crop Irrigation

An alternative to utilization of high-quality, fresh ground and surface water for irrigation is to maximize the use of treated and recycled waters for energy crop production. A particularly interesting option would turn liabilities into benefits. For example, the State of North Carolina (NC) is the second largest pork producing state in the United States. Alongside the growth of the pork production is the generation of a large quantity of liquid animal waste. This waste needs to be utilized in an environmentally sustainable manner. This waste from swine production had typically been treated in anaerobic wastewater lagoons. During the 1990s, tropical storms and hurricanes caused many lagoons to fail and spill excess nutrients into surface waters. These lagoon failures along with public outcry led to a search for better treatment methods in 1997 (NC, 1997). During this search, the State of NC along with major pork producers entered into an agreement to investigate new treatment systems for swine wastewater treatment and management. Results from this agreement produced a system that could meet the defined environmental standards (Vanotti *et al.*, 2007). The new system removed solids and significantly reduced the nutrient concentration in effluent waters. This treatment option would essentially convert the on-farm anaerobic lagoons into water storage facilities. These water storage facilities would be easier to manage for water application to crops due to the significantly lower nutrient concentrations. The NC Department of Agriculture estimated that there were approximately 4000 active swine wastewater lagoons on 2500 farms. With an average lagoon size of approximately 1 ha, each would store approximately 23 000 m^3. Statewide, the potential increased water available for potential energy crop production would provide approximately 92 million m^3 of water storage. This quantity of water applied at an average application depth of 150 mm (USDA-NASS, 2004) would provide enough water to irrigate approximately 60 000 ha. This area is potentially double the existing irrigated area in NC and provides an excellent resource for producing biomass energy crops. Stone *et al.* (2008) conducted a study in North Carolina comparing treated effluent with conventional fertilizers for bermudagrass production. They found using treated swine wastewater effluent produced significantly higher bermudagrass hay yields. Cantrell *et al.* (2009) analyzed the biomass samples from the Stone *et al.* (2008) study for the energy content and found with the increased biomass quantity, there was more biomass energy potential from the bermudagrass grown with treated wastewater effluent. Thus, irrigation with treated wastewater provides a means to irrigate future bioenergy crops without burdening local water resources, while at the same time not excessively overloading the crops with nutrients. This utilization of treated wastewater could offset the impacts of utilizing higher quality well and surface water for growing energy crops in regions of the country that utilize similar swine wastewater treatment systems.

Controlled Drainage and Water Table Management

Increased production of energy crops such as maize in the Midwestern states would require additional use of fertilizers to enhance productivity. The NRC (2008) reported that fertilizers applied to increase agriculture yields can result in excess nutrients flowing into waterways via surface runoff and infiltration to groundwater, and will have a significant impact on water quality. Excess nitrogen in the Mississippi River system is known to be a major cause of the oxygen-starved "dead zone" in the Gulf of Mexico. In much of the upper Midwest region, agricultural drainage has been a major contributor to the success of agricultural production. In the United States, Pavelis (1987) estimated that there were over 20 Mha of agricultural drainage in the Midwestern states and that the Southeast and Atlantic regions had more than 9 Mha.

The overall reason for implementing agricultural drainage was to enhance crop production. Drainage systems allowed timely seedbed preparation, planting, harvesting and other field operations while protecting field crops from extended periods of flooded soil conditions.

While there are many positive aspects of land drainage, there are potential adverse aspects as well (Rabalias *et al.*, 1996; Kanwar, 2006; Jaynes and Colvin, 2006; Hunt *et al.*, 2008). Excess nutrients in drainage water can lead to local water quality problems and potentially contribute to hypoxia in larger water bodies, coastal estuaries, and the Gulf of Mexico. Strategies are needed that reduce nutrient loads while maintaining adequate drainage for crop production.

These improved management systems are often referred to as controlled drainage or water table management. These systems utilize structures to control the water levels in agricultural fields, drainage ditches, and even watersheds (Gilliam and Skaggs, 1985; Stone *et al.*, 1992; Evans *et al.*, 1992; Madramootoo *et al.*, 2007). These systems allow timely drawdown of water levels for agricultural operations and prevent excessive nutrient-rich water from being discharged. They can increase the water storage capacity in the soil profile and increase crop water use efficiency (Stampfli and Madramootoo, 2006).

The implementation of controlled drainage systems has been identified as a tool to mitigate the adverse effects of uncontrolled drainage (Thomas *et al.*, 1992; Thomas *et al.*, 1995; Fausey, 2004; Fouss *et al.*, 2004). To address the potential adverse effects of uncontrolled drainage, the Agricultural Drainage Management Systems Task Force (ADMS) was established in 2003 to improve drainage practices and reduce adverse impacts while enhancing crop production and conserving water (http://hostedweb.cfaes.ohio-state.edu/usdasdru/ADMS/ADMSindex.htm). Controlled drainage decreases the peak outflow (Amatya *et al.*, 1998; Tan *et al.*, 1999) from drainage systems and reduces nitrate-nitrogen concentration in drainage outflows (Mejia and Madramootoo, 1998; Elmi *et al.*, 2002; Evans *et al.*, 2007). In a review of several studies, Evans *et al.* (1995) reported nitrogen and phosphorus reductions of 30% and 50% resulting from controlled drainage. Skaggs *et al.* (2010) reported on the effects of controlled drainage on water and nitrogen balances in drained lands. From the literature, they found that controlled drainage reduced drainage volumes and N losses in drainage waters by 17% to over 80%, depending on soil properties, crops, drainage intensities, control strategies, and location. The nitrogen reductions were attributed to denitrification both in the soil profile and in the reduced zones along the seepage paths. Implementation of these systems could improve and mitigate potential water quality problems associated with increased production of potential biofuel crops identified by the National Research Council (NRC, 2008).

Biofuel Generation via Thermochemical Conversion

While ethanol production from maize grain seems to be the current focus of most biofuel production efforts, we have established that if maize grain ethanol is the sole biofuel, then an immense amount of water is needed to supply the Billion-Ton Vision. Thus, endeavors must be made to convert biomass feedstocks beyond maize grain; these feedstocks can include cellulosic biomass as well as agricultural residuals, animal manures, and municipal solid waste (MSW). Even though these feedstocks will eventually be converted biochemically (fermentation), these processes leave a carbon-rich residual that still contains inherent energy; thus, the feedstocks are not broken down to their full energetic potential. Additionally, the biochemical conversion process by nature has a huge water requirement, thereby adding to the sustainability concerns.

Compared to traditional biochemical conversion processes, thermochemical conversion processing of bioenergy crops holds the promise of better feedstock versatility, improved conversion efficiency, greater energy yields, and enormously lower water use. For this type of high-temperature conversion to produce a liquid biofuel, two options stand out—pyrolysis and gasification. Pyrolysis takes advantage of high temperatures and an inert atmosphere to convert organic (carbonaceous) material into one primary product: either a carbonized solid similar to charcoal (bio-char) or a combustible bio-oil. The bio-char is amenable as a feedstock ("green coal") for existing coal combustion and gasification plants.

The bio-oil has potential to be used as a combustible heat source and fungible hydrocarbon fuel. However, the major limitation is the instability of the bio-oil inherent with its acidity, high water content, high oxygen content, and reactive components (e.g., char particulates). Successful stabilization and upgrading of bio-oil would allow for easier assimilation by both existing combustion applications and petroleum refinery infrastructure. Upgrading bio-oils was successfully demonstrated as a jet fuel during a hydroplane test run (http://bioweb.sungrant.org/Technical/Biopower/Technologies/Pyrolysis/Pyrolysis+Oil/Pyrolysis+Oil.htm). This test run, conducted by Honeywell-UOP and Boeing, used a 10% renewable jet fuel containing 2% aromatics from upgraded woody bio-oil. The time to certification for bio-oil fuel substitutes is anticipated to take 5 years (http://bioweb.sungrant.org/Technical/Biopower/Technologies/Pyrolysis/Pyrolysis+Oil/Pyrolysis+Oil.htm). With other commercialization and research and development projects underway, pyrolysis has the potential for farm- and crop-scale implementation (Cantrell *et al.*, 2008).

Gasification is the process that uses gasification media (e.g., steam, air, or oxygen) at high temperatures to convert organic materials into gaseous products. Gasification converts the chemical energy found in the carbon bonds into heat and a combustible gas consisting primarily of CO and H_2, or synthesis gas. This "syngas" product can be purified and used in a variety of ways: heat and power generation, transportation fuels, and chemical intermediates (McKendry, 2002a; Cantrell *et al.*, 2008). For gasification to be effective, the biomass moisture content should be below 10–15% (McKendry, 2002b); a moisture content of about 30% impedes ignition and reduces the heating value of the product gas. Thus, use of this type of bioenergy conversion process eliminates the need for a water input. In fact, recycling and recovering the heat in the product gas as a means to drive away the moisture in the feedstock would be one way farmers and practitioners could recover water without additional energy demands, making the entire gasification process sustainable for bioenergy production.

Conclusions

The expanded production of agricultural crops for bioenergy production has introduced new challenges for management of water. Water is now being called upon for bioenergy production, thereby stretching an already vital resource. Water availability has been widely presumed as a nonlimiting factor in the discussion of bioenergy crop production. However, water is a limited resource. Many parts of the world are experiencing water scarcities complicated by a growing population. Water scarcities are not only impacting humans and agriculture for food production but also the environment.

Bioenergy biomass crop production is highly dependent on water. Thus, weather variability including droughts and floods can greatly impact bioenergy availability. Climate change is impacting water resources throughout the world. In the Western United States, water supplies are highly vulnerable to climatic changes that affect snowpack. Over the last century, runoff from snowmelt in the Western United States is occurring earlier and shifting soil moisture recharge and evapotranspiration earlier in the year. Weather extremes (droughts and flooding) are also affecting other areas of the United States. Flooding and droughts have been occurring with a higher frequency in the Central United States with a higher percentage of extreme events occurring in the Western United States and to some extent the Eastern United States. These climatic extremes highlight the potential vulnerabilities and disruptions in future bioenergy supplies.

Caution should be used in shifting to alternative biomass crops without considering their impact on water resources. Introducing tree plantations and woody crops can significantly increase water use and reduce both runoff and stream flow. Reduced flows may be gradual and initially unnoticed but can be significant over time. Shifting agronomic crops can also impact seasonal water demands and off-site nutrient movement.

Maize and sugarcane are the current major crops used for ethanol production. The water requirements to produce maize grain for ethanol are much higher than to produce sugarcane. The main reason for the greater water requirements for maize grain was that only grain is currently utilized for ethanol production. The water requirements for maize grain production to meet the US-DOE Billion-Ton Vision would increase approximately sixfold to meet the 2030 production goals and may put tremendous stress on current water resources. As new technologies for cellulosic conversion of biomass for ethanol production are demonstrated and improved, the relative difference between the crop water requirements may be reduced. Furthermore, thermochemical conversion utilizing a wider variety of feedstocks for bioenergy may emerge as a more sustainable option.

Alternative water management and technology systems can be implemented to improve water availability and produce bioenergy. New treatment systems for livestock waste offer the potential for utilizing treated effluent to irrigation and grow bioenergy crops. Controlled drainage can increase plant available water and improve water quality. The projected increase in global population and competition for water resources among urban, industrial, economic, and environmental sectors will impact the water available for food and bioenergy production. Consequently, water needs to be incorporated into discussions and decisions related to the implementation and technology for bioenergy. To be sustainable, biomass crop production for bioenergy must conserve and protect natural resources—including fresh water.

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