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The potential impacts of biomass feedstock production on water resource availability

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ABSTRACT

Biofuels are a major topic of global interest and technology development. Whereas bioenergy crop production is highly dependent on water, bioenergy development requires effective allocation and management of water. The objectives of this investigation were to assess the bioenergy production relative to the impacts on water resource related factors: (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. Shifts to alternative bioenergy crops with greater water demand may produce unintended consequences for both water resources and energy feedstocks. Sugarcane and corn require 458 and 2036 m^3 water/m^3 ethanol produced, respectively. The water requirements for corn grain production to meet the US-DOE Billion-Ton Vision may increase approximately 6-fold from 8.6 to 50.1 km^3. Furthermore, climate change is impacting water resources throughout the world. In the western US, runoff from snowmelt is occurring earlier altering the timing of water availability. Weather extremes, both drought and flooding, have occurred more frequently over the last 30 years than the previous 100 years. All of these weather events impact bioenergy crop production. These events may be partially mitigated by alternative water management systems that offer potential for more effective water use and conservation. A few potential alternatives include controlled drainage and new next-generation livestock waste treatment systems. Controlled drainage can increase water available to plants and simultaneously improve water quality. New livestock waste treatments systems offer the potential to utilize treated wastewater to produce bioenergy crops. New technologies for cellulosic biomass conversion via thermochemical conversion offer the potential for using more diverse feedstocks with dramatically reduced water requirements. The development of bioenergy feedstocks in the US and throughout the world should carefully consider water resource limitations and their critical connections to ecosystem integrity and sustainability of human food.

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1. Introduction

Biofuels are a major area of interest and technology development globally. The US Department of Energy (US-DOE) implemented the Biofuels Initiative with a target goal of replacing 30% of current levels of gasoline with biofuels by 2030 (US-DOE, 2008a). As such, biofuel production has become intimately connected to global agriculture. It has also placed new demands on agriculture. These demands include increasing crop yield, developing energy crops, effectively utilizing livestock manures, and conserving natural resources. These demands are clearly seen in corn used for ethanol production. In 2002–2003, ethanol accounted for 10% of corn use. By 2007–2008, it accounted for 25%. Additionally, corn demands for traditional uses are projected to increase slightly during the coming years (USDA-ERS, 2008, Fig. 1). The increasing demand for corn for ethanol production has resulted in tightening of the global corn supply and demand balance (Trostle, 2008). The world aggregate stocks of grains and oil seeds, as reported by Trostle (2008), began to decline in 1999 due to (1) a long-term trend in slower production growth and (2) a rapidly increasing growth in demand. The stock-to-use ratios were further impacted in many parts of the world by adverse weather conditions. This increased demand has resulted in the lowest global stock-to-use ratio for grains and annual oilseeds in nearly four decades (Trostle, 2008).

In order to meet increasing biofuel demands, agriculture will require greater land and water resources. This will likely require: (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) increasing the use of fertilizer and agrochemicals (Uhlenbrook, 2007). Ultimately, all these actions will heighten potential agricultural impacts on natural resources. If local agriculture shifts to biofuel/bioenergy crops that require more than

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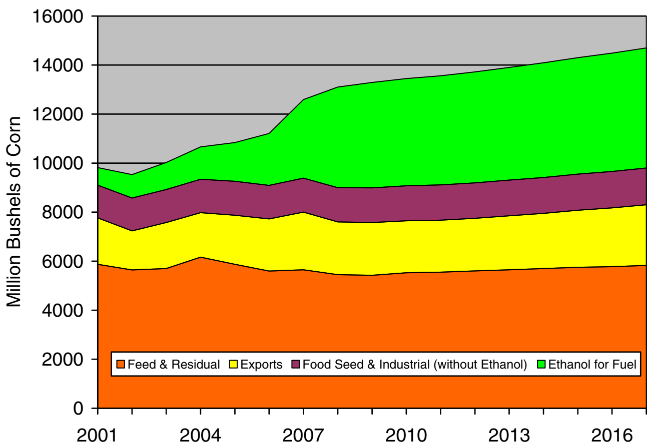

Fig. 1. Projected US Corn use (from ERS, 2008).

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.

1.1. Fresh water

Fresh water is unique 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 icecaps 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 fresh water 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.

Fresh water scarcities have already been reported in many parts of the world (Postel, 2000; Brown, 2003). Further complicating these fresh water 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 law suits, conflicts, and wars. Civilizations have risen and fallen because of the availability or lack of water (Sadler et al., 1993; Postel, 2001; Montgomery, 2007; Diamond, 2005). In 2008, the United Nations Secretary General (ABC News, 2008) called on the world leaders both to place the looming crisis over water shortages at the top of the global agenda and to take actions to prevent conflicts over scarce supplies. He further pointed out that "too often, where we need water we find guns instead," and as an example he stated that the current conflict in the Darfur region of Sudan was touched off by drought.

Water availability has not only directly impacted humans and civilizations, but it has impacted the environment. In many areas of the world, fresh water 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 over utilized to meet societal demands (Falkenmark and Lannerstad, 2005; Brown, 2001). 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 to catastrophic underlying problems if bioenergy development were pursued in the US 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 paper, we review the potential impacts 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.

2. Climate and weather impacts on water supplies for biomass production

2.1. 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 Nino 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 found that both winter wheat and maize can be affected by climate change. They found for maize a 5–10% yield reduction and similar yield reduction in wheat. They suggested that alternative adaptation strategies such as changing planting dates be implemented that would assist in counterbalancing the impacts of a warmer and drier environment.

The US Office of Technology Assessment (US 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 US 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 et al. (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 US 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 mid-winter 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.

2.2. 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 exacerbated 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 US. The Western and Eastern US had a higher percentage of extreme events. They found that of four large pluvial events occurring in the US during their study period – three occurred during the past 30 years.

In 2008, the major corn producing states of the upper Mid-west 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 Mid-west was affected by similar floods. Both events exceeded the historical 100-year return interval.

Additionally, flood water has the potential for enormous impacts on downstream water quality. The National Research Council (NRC, 2007) 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 the potential for 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.

2.3. Drought

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 multi-decadal durations and greater spatial extent than those of the twentieth century. Whether from preindustrial, geophysical, or current hypothesized climate change, the central US has and will continue to be vulnerable to droughts.

Like many other areas of the world, the US has recently had extended droughts affecting various areas of the country. While there are too many weather related droughts to address individually, a few can be highlighted that would have a potential impact on future energy crop production. Izaurralde et al. (2005) reported that the temperate and subtropical southeastern US states had the potential for maximum annual biomass net primary production growth rates. The southeastern US has one of the highest renewable water supplies in the US (Solley et al., 1998, Fig. 2). However, a recent multi-year period with intermittent drought in the Southern Appalachian Mountains reduced the water levels to critical

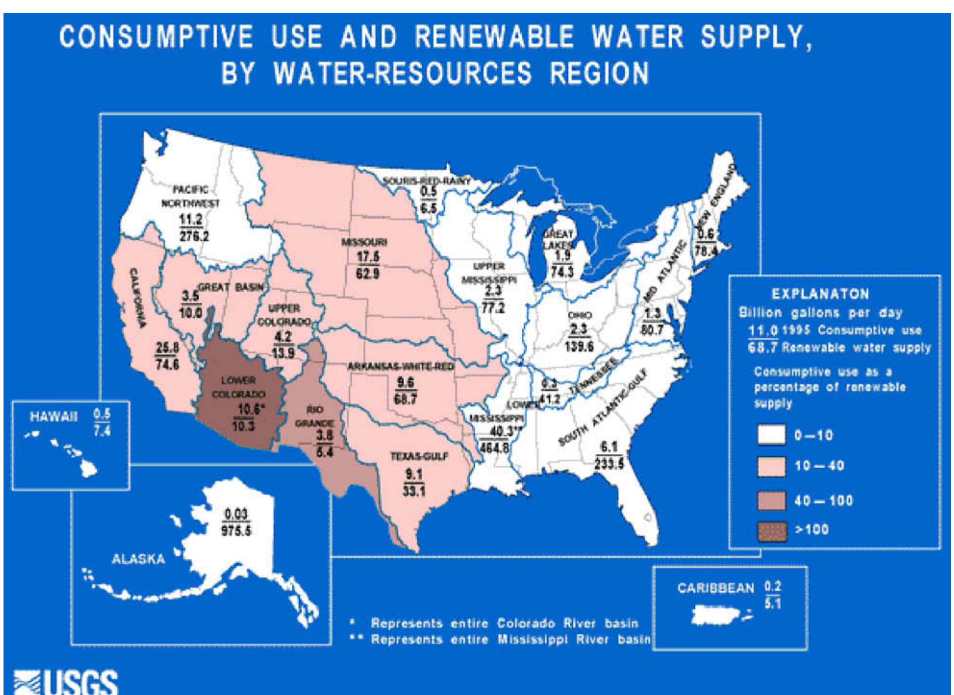

Fig. 2. Comparisons of average consumptive use and renewable water supply for the 21 water resources regions of the US, Puerto Rico, and US Virgin Islands. Adapted from USGS 1995 (http://water.usgs.gov/watuse/misc/consuse-renewable.html).

levels in northern Georgia reservoirs. This drought has intensified disputes over water rights and allocations between the states of Georgia, Florida, and Alabama. These reservoirs provide water for electrical power generation and are the major source of drinking water for the metropolitan Atlanta area (population > 5,000,000). Florida and Alabama have sued Georgia because water flows to Alabama and Florida have been reduced affecting downstream power generation and aquatic life. The specifics of the law suits are beyond the scope of this report. However, it is important to note that watersheds in southwestern Georgia were targeted to contribute water to the affected rivers. During declared droughts, farmers 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 producing region of the US, farmers in Nebraska were paid not to irrigate along the Republican and Platte Rivers. This was also a result of multi-year drought conditions (US-Water News Online, 2005; NE-DNR, 2005; NE-FSA, 2007). Although these reductions in irrigation in the Southeastern and Mid-western US are troubling for agricultural production, irrigation reductions are more common in the Western US. In many Western US states, cities have purchased water rights from farmers to meet urban and industrial needs (Brown, 2003). These droughts throughout the US 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.

2.4. 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 of 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 corn 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 corn yields and yearly oil imports (Fig. 3). They found through analyzing the distributions that variations of oil imports were less than half those of annual corn yields. They concluded that corn production was more volatile than oil imports. They attributed most of this increased volatility of corn and ethanol production on their dependency on weather. They further concluded that based on their historical analysis that displacing gasoline with ethanol would be exchanging geo-political risk with yield risks.

Climate change predictions all point toward increased variability in temperature extremes and rainfall extremes. If these

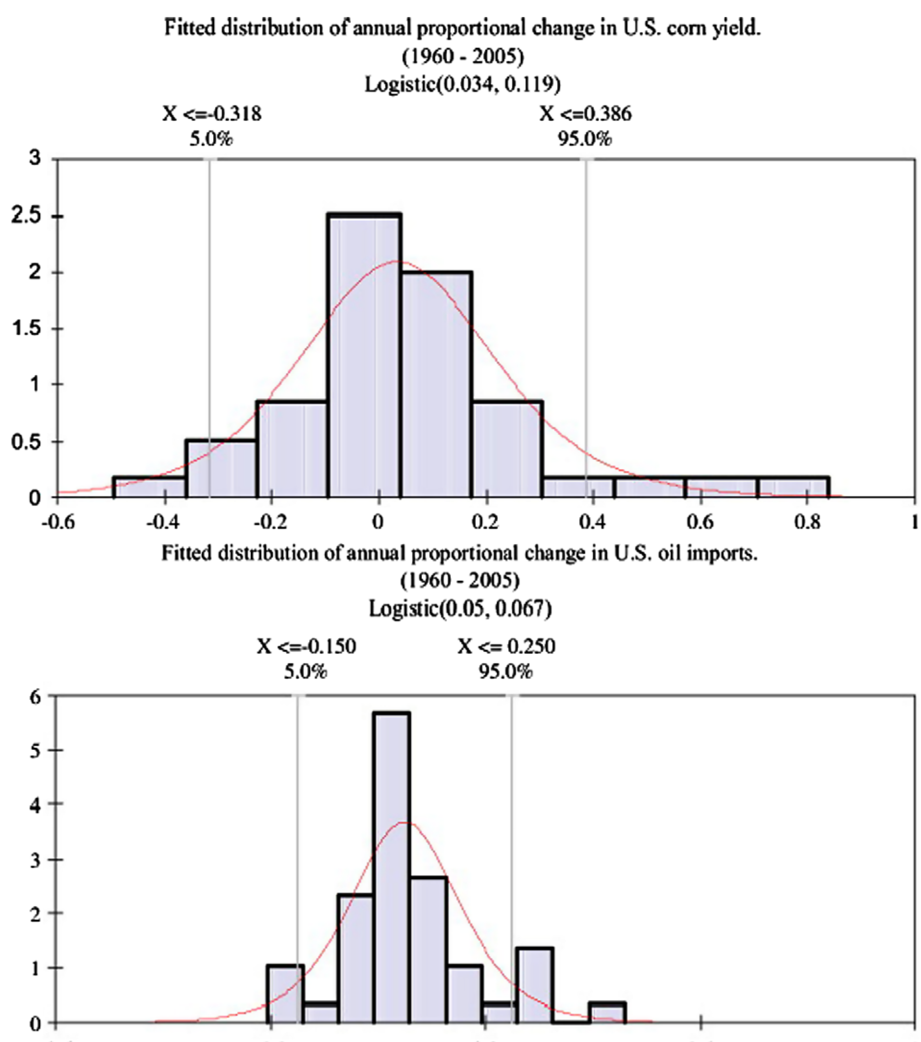

Fig. 3. The historical reliability of corn yields and oil imports. Fitted distributions and confidence intervals for the year-to-year change in corn production (Eaves and Eaves, 2007).

extremes related to predicted climate change were incorporated into Eaves and Eaves (2007) model, there would be little doubt that there would be increases in the variability of grain production.

Climate change is predicted to have significant impacts on agricultural production in the future. Many of these changes have been researched related to 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.

3. Water use for major bioenergy crops – 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 US, it is estimated that agricultural water consumption for irrigation is 80% of the total water consumed (Solley et al., 1998).

The recent escalation of crude oil prices and the initiatives for alternative fuels to reduce industrialized nations carbon dioxide emissions has many countries searching for biomass crops to produce ethanol for fuel (US-DOE, 2008b). Currently, the two major crops used for ethanol production are sugar cane and corn in Brazil and the US, respectively. These crops were analyzed and compared as currently managed to determine their relative water utilization during the production of the biomass feedstocks.

3.1. Sugar cane production in Brazil

Brazil is recognized as the world's second largest producer of ethanol (DOE-EIA, 2007; Trostle, 2008). Brazil 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 the nation's cars made in Brazil were able to run on ethanol. The primary crop that Brazil uses for ethanol production is sugar cane (*Saccharum*). Brazil is the world's largest producer of sugarcane (FAO, 2008: 420,121,000 metric tons). Sugar cane 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/ton of cane production. The sugar cane growing season is year round, and the annual requirements for sugarcane production are approximately 1500–2500 mm/year (Goldemberg et al., 2008; Moreira, 2007). The majority of the sugar cane 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, sugar cane 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 (approximately 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). The Pacific Institute (2008) reported that Brazil had the largest annual renewable freshwater supply in the world (8233 km^3/year).

The processing and converting of sugarcane to ethanol requires large amounts of water also 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/ton 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/ton in the 1990s to reported values for 2004 of 1.83 m^3/ton (Goldemberg et al., 2008).

3.2. Corn production in US

In the US, the current major source of ethanol production is corn. 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 corn went into ethanol production (see Fig. 1). This was an 18% increase from only 7% in 2001 (NCGA, 2002, web site). Although these figures make it appear that a large tonnage of the US corn crop was being diverted into the production of ethanol and away from other uses, the overall impact was offset by increases in corn production and storage drawdown (Trostle, 2008). All other uses of corn have remained approximately unchanged (2001–2007), except for a small decrease in corn exports.

In the US, the vast majority of corn is produced in the mid-western states (Table 1, USDA-NASS, 2004). Many of the corn producing states (Iowa, Illinois, etc.) have adequate annual rainfall associated with deep rich soils with adequate water holding capacity to produce corn without supplemental irrigation. However, other corn producing states in the Mid-west and High Plains utilize considerable irrigation to produce corn (Table 2, e.g., Nebraska, Kansas). Here, the major source of irrigation water in the High Plains region is the 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 million hectors 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 1930, 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 corn producing states. Nebraska was third largest corn producing state (3.6 million hectors), with Kansas, Texas, and Colorado also producing over 0.5 million hectors each (NCGA and NASS data). USDA-NASS (2004) estimated that 19% of all irrigation in the US was for corn production. The USDA-NASS (2004) also estimated that the states overlying the High Plains Aquifer (Nebraska, Kansas, Colorado,

Table 1
Top 10 corn producing states from the 2002 census of agriculture and 2008 NASS.

Geographic area	2008 NASS	2002 census of agriculture					
	Area (ha)	Number of farms	Area (ha)	Number of irrigated land farms	Irrigated land area (ha)	% of total area irrigated	Rank in irrigation
US	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

Table 2
Top 10 irrigated corn producing states from the 2002 census of agriculture and 2008 NASS.

State	2008 NASS	2002 census of agriculture					
	Area (ha)	Number of farms	Area (ha)	Number of irrigated land farms	Irrigated land area (ha)	% of total area irrigated	Rank in corn 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

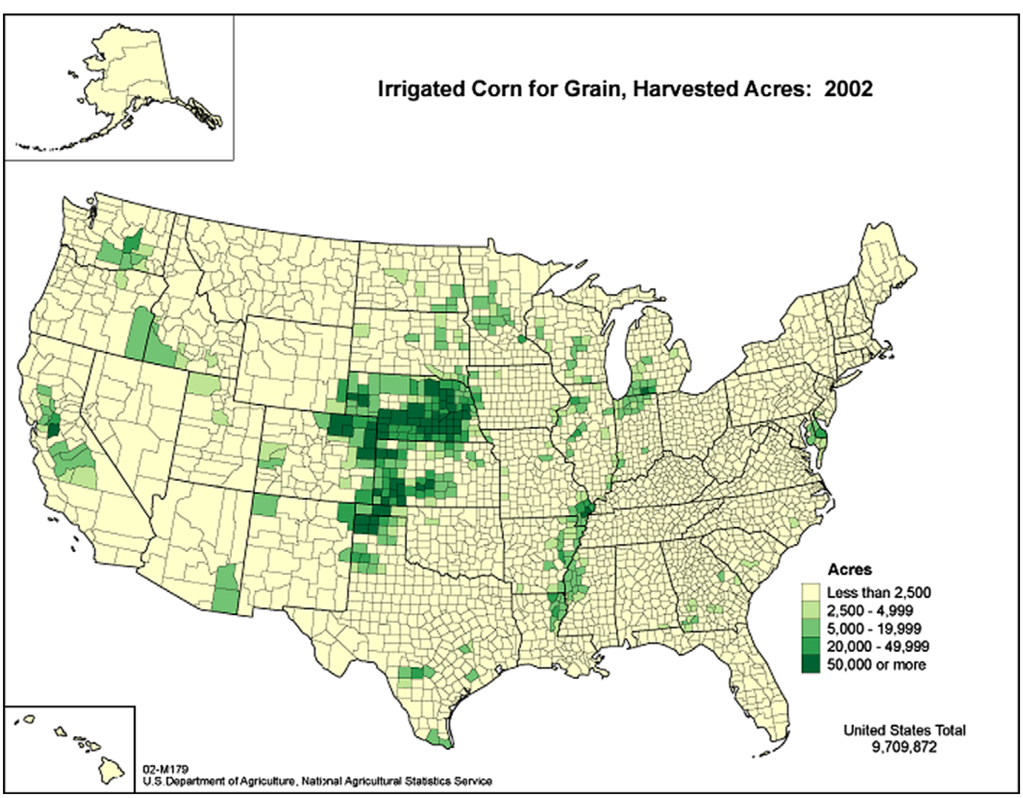

Fig. 4. US Irrigation corn for grain. http://www.agcensus.usda.gov/Publications/2002/Ag_Atlas_Maps/Crops_and_Plants/index.asp.

Table 3
Comparison of water requirements for ethanol production from corn grain, sugarcane, and other potential energy crops.*

Crop	Water requirements (m^3 water/Mg crop)	Biofuel conversion (L fuel/Mg crop)	Crop water requirement for biofuel (m^3 water/Mg fuel)	Crop water requirement per unit energy (m^3 water/GJ)
Ethanol				
World corn (grain)	833	409	2580	97
World sugarcane	154	334	580	22
Nebraska corn (grain)	634	409	1968	74
Corn stover	634	326	2465	92
Corn 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	259.0
Canola	1798	415	4923	130.2

* World Corn and sugarcane estimates from Postel (1998); Nebraska corn estimates from Nebraska Corn 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).

and Texas) accounted for approximately 90% of irrigated US corn acreage (Fig. 4).

In Nebraska, the third largest US corn producing state, irrigated corn averages 70% of the total corn acreage (Nebraska Corn Board, 2008, and Table 2). In 2007, the Nebraska Corn Board (2008) reported average corn yields of 10 Mg/ha (160 bu/ac). The mean 2007 corn yield from Nebraska of 10 Mg/ha would require approximately 635 mm (approximately 25 in) of water. Combining the yield with the water requirements for the production would result in approximately 635 m^3 water/Mg grain. If this is combined with a corn to ethanol conversion rate of 25.9 L ethanol/Mg grain (2.5 gal ethanol/bu corn) it would result in a ratio of 1968 m^3 water/Mg (or 1553 m^3 water/m^3) ethanol. In most of the nonirrigated corn producing areas, the water would be from rainfall and moisture stored in the soil. In irrigated corn production regions such as Nebraska, the NASS reported that the average irrigation for corn production was 365 mm (1.2 ac-ft). This irrigation water requirement would be approximately half of the water needed for corn production. Most of this water in the region would come from the High Plains Aquifer that is already experiencing rapidly declining water levels.

3.3. Comparison of sugar cane and corn water usage

For comparison of corn water use for ethanol production with sugarcane, we used the world average production estimates for sugar cane and corn grain from Postel (1998), We calculated and contrasted the estimates for water requirements for crop production to produce ethanol (Table 3). Ethanol conversion from biomass to ethanol was estimated per Mg of corn grain and sugarcane, as 409 and 334 L of ethanol, respectively (US-DOE, 2008a,b; James, 2008). The resulting calculated water requirements were 2580 m^3 water per Mg (2036 m^3 water/m^3) ethanol for corn grain and 580 m^3 water per Mg (458 m^3 water/m^3) ethanol for sugarcane. They are also photosynthetically very different. The water requirements to produce corn grain were much higher than water required for sugarcane. The main reason for the greater water requirements for corn grain was that only grain (not the entire plant including stalk and leaves) 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 corn biomass that can be used is limited by soil resource issues such as erosion and nutrient depletion (Mann et al., 2002; Doran et al., 1984; Wilhelm et al., 2004). Again, the large disparity was mainly due to only grain being utilized for ethanol production with corn. Additionally, corn has a much shorter growing season than sugarcane. This shorter growing season with higher water demands makes corn 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).

3.4. Water demands for Billion-Ton Vision

A joint authored report by the US Departments of Energy and Agriculture was recently published entitled "The Technical Feasibility of a Billion-Ton Annual Supply of Biomass Feedstock for Bioenergy and Bioproducts Industry" (US-DOE, 2005). This report looked at aspects of biomass potential for bioenergy production in the US. The report does not address the water resource requirements for the Billion-Ton Vision; 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 (2005) study assumed that the US agricultural lands could currently produce 15 million dry tons of grain for biofuel production. It also further assumed that 87 million dry tons of grain could be produced in the US by 2030. The study assumed that water and nutrients would be available to support the Vision. If we assume the same water demands as that for Nebraska corn (634 m^3 H_2O/Mg corn), the Vision requires 8.64×10^9 m^3 (7 million ac-ft water), currently, and 5.01×10^{10} m^3 (41 million ac-ft water) by 2030. This is approximately a 6-fold increase in water demand for production to meet the goals in 2030. An underlying assumption of the Billion-Ton Vision (US-DOE, 2005) was that grain yields would increased by 50% by 2030. The Vision identified a key requirement for attaining targeted increases in yields was for sufficient water to be available. Even if geneticists obtained a doubling in water use efficiency to complement the increased yields, the needed water 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.

4. 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 US 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 access their impact.

4.1. 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: corn, wheat, etc.; perennial grasses: switchgrass, Miscanthus, etc.; and fast growing trees: popular, 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 (Singh Prasad et al., 2007). Sweet sorghum has greater water use efficiency, is more drought tolerant, and requires only 36% the nitrogen fertilizer required by corn. 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 grass lands to forest could reduced 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 (Fig. 5) 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 grass lands to pine plantations resulted in an increase of 40–70% in evapotranspiration.

Reijnders (2006) reported that fresh water 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.

4.2. 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 is the second largest pork producing state

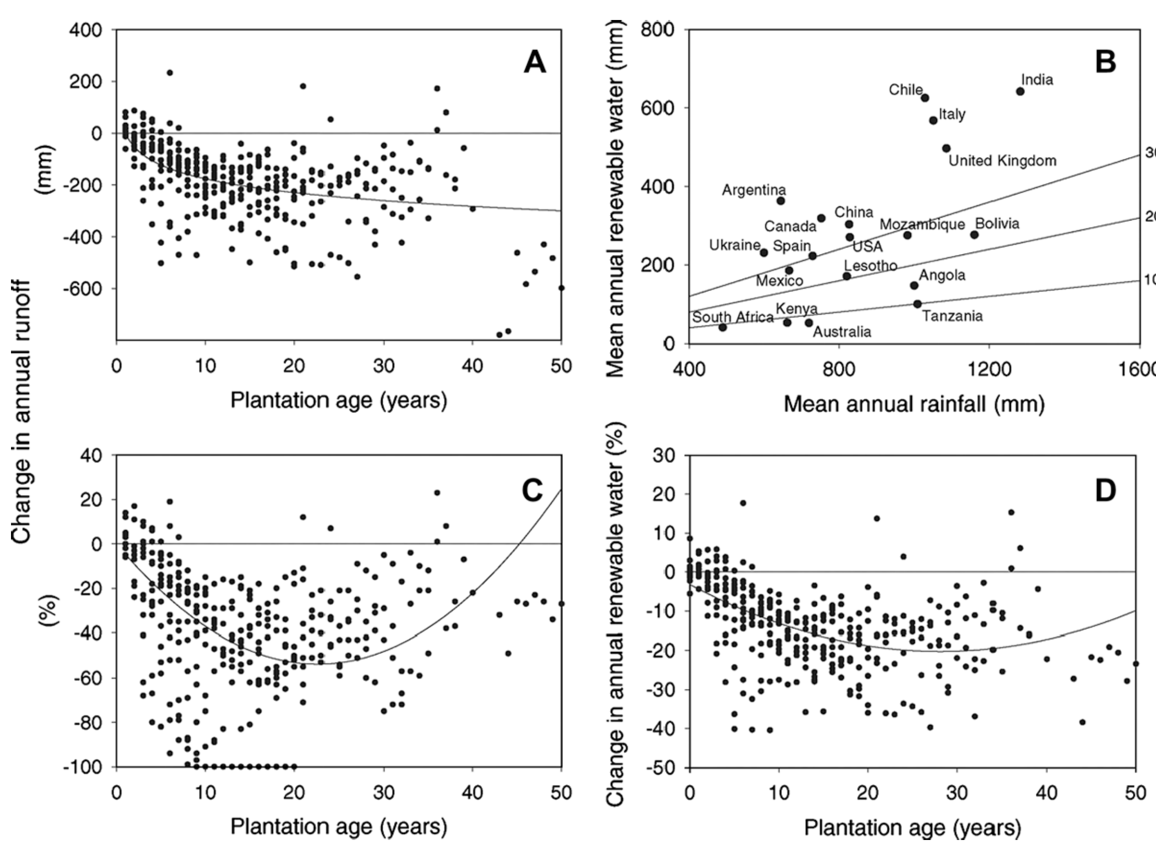

Fig. 5. Changes in stream flow and annual renewable water as a function of plantation age, and the relative abundance of renewable water by country. From Jackson et al. (2005).

in the US. 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 system for swine wastewater treatment and management. Results from this agreement produced a system that could meet the defined environmental standards. 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 waste water lagoons on 2500 farms. With an average lagoon size of approximately one hectare, 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 waste water could offset the impacts of utilizing higher quality well and surface waters for growing energy crops in regions of the country that utilize similar swine wastewater treatment systems.

4.3. Controlled drainage and water table management

Increased production of energy crops such as corn in the Mid-western states would require additional use of fertilizers to enhance productivity. The NRC (2007) 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 many areas of the world, agricultural drainage has been a major contributor to the success of agricultural production. In the US, Pavelis (1987) estimated that there were over 20 million ha of agricultural drainage in the Mid-western states and that the Southeastern and Atlantic regions had more than 9 million ha.

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 waters 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, 1995; Fausey, 2004; Fouss et al., 2004). 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 (Elmi et al., 2002; Mejia and Madramootoo, 1998; 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. Implementation of these systems could improve and mitigate potential water quality problems associated increased production of biofuel crops identified by the National Research Council (NRC, 2007).

4.4. Biofuel generation via thermochemical conversion

While ethanol production from corn grain seems to be the current focus of most biofuel production efforts, we have established that if corn 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 corn 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 can be used as a feedstock ("green coal") for existing coal combustion and gasification plants. The bio-oil may be used in combustion furnaces and boiler systems. One such commercial system has demonstrated it can generate heat by regularly using bio-oil (Czernik and Bridgwater, 2004). For bio-oil to be used as a transportation fuel, upgrading and refining would be necessary to decrease the oxygen content, remove alkalis, and create a more consistent product. Pyrolysis has the potential for farm and crop scale implementation (Cantrell et al., 2008).

Gasification is the process that converts organic materials into gaseous products using gasification media at high temperatures such as air, oxygen, or steam. 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). The syngas can be converted into a combustible liquid hydrocarbon like methanol, ethanol, and diesel using Fischer–Tropsche catalytic driven reactions. For gasification to be effective, the biomass moisture content should be below 10–15% (McKendry, 2002b); a moisture content 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.

5. Conclusions

The expanded production of agricultural crops for bioenergy production has introduced new challenges for management of water. Water availability has been widely presumed 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. Water is now being called upon for bioenergy production thereby already stretching a vital resource.

The biomass crop production for bioenergy is highly dependent on water. Thus weather variability including droughts and floods can greatly impact bioenergy availability. Weather induced changes in corn production for ethanol were twice as variable as oil imports for the last 40 years, indicating potential vulnerabilities and disruptions in 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.

Climate change is impacting water resources throughout the world. In the Western US, water supplies are highly vulnerable to climatic changes that affect snowpack. Over the last century, runoff from snowmelt in the Western US 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 US. Flooding and droughts have been occurring with a higher frequency in the Central US with a higher percentage of extreme events occurring in the western US and to some extent the Eastern US.

Corn and sugarcane are the current major crops used for ethanol production. The water requirements to produce corn grain for ethanol are much higher than to produce sugarcane. The main reason for the greater water requirements for corn grain was that only grain is currently utilized for ethanol production. The water requirements for corn grain production to meet the US-DOE Billion-Ton Vision would increase approximately 6-fold to meet the 2030 production goals and would 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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